The Institution is not, as a body, responsible for the opinions expressed by individual authors or speakers.

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CORRIGENDA.

Vol. 62, page 841, col. 2, line 12: For "$0{\cdot}2\mu F$" *read* "$2\mu F$."

" , page 914, Table 5: The last three lines *should read*:

$\frac{1}{16}$	$\frac{1}{2}$	0·03125	0·2016	110·7	3 542
	$\frac{3}{4}$	0·0469	0·3024	158·9	3 388
	1	0·0625	0·4032	205·8	3 292

Vol. 63, page 152, col. 1, line 13 from bottom: *Delete* asterisk after $\doteqdot \rho(1 - p^2 L\gamma)^2$.

" , page 207, col. 2, last line: For "speed" *read* "field current."

" , page 210, col. 1, equation (4): For "$(Zpn)^2 T$" *read* "$(Zpn)^2 T'$."

" , page 431, col. 1, line 21: After "density" *add* "at 40 cycles."

" , page 439, col. 1, line 31: For "amount" *read* "size."

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INAUGURAL ADDRESS

By WILLIAM B. WOODHOUSE, President.

(*Address delivered before* THE INSTITUTION, *23rd October*, 1924.)

To be elected President of the Institution of Electrical Engineers is an honour carrying with it a measure of responsibility, of which I am deeply conscious. It is an honour which I value not only as a personal one but as, in some degree, a recognition of the importance of the branch of electrical engineering in which I am engaged. I thank you very much.

THE INSTITUTION.

The Institution, to be fully representative of the activities of its members, must engage in numerous and diverse works. Its rapid growth in recent years has been due, I think, to the appreciation of this necessity and to the policy of the Council of aiding, by a frank and helpful recognition of sectional interests, the creation of other organizations to meet new needs as they arise.

Amongst such bodies may be mentioned the British Engineering Standards Association, whose good work is yearly showing itself to be of more and more value; the Electrical Research Association, whose contributions to knowledge will, I hope, continue to flow in an increasing volume; and the Electrical Development Association, whose mission is not only to educate the public in matters electrical but to emphasize the mutual interdependence of various sectional interests on one another.

The Wireless Section of the Institution, the Local Centres, the Centres overseas and the numerous special Committees of the Council all indicate a policy of enlisting the active support and direct efforts of as large a number of members as possible in the great work of development which the Institution has undertaken.

The continued work of the body of members in the past has resulted in a general increase of knowledge, in which the whole world shares, and in a variety of ways has helped to improve the status of the electrical engineer. Our duty each in turn is to repay, so far as we can by working for the common good, the benefits which we have received from the work of others.

The granting of the Royal Charter to the Institution was a gracious recognition by His Majesty the King of the distinguished position which the Institution now holds. During the past year, in connection with the World Power Conference, a further mark of Royal favour was shown, by the Garden Party given by His Majesty to representatives of the Institution and of the foreign delegates to the Conference. I am sure that all members will value this additional recognition.

EDUCATION.

The electricity supply industry, the branch of electrical engineering in which I have spent the greater part of my professional life, is now reaching a stage of development at which the magnitude and nature of the problems to be dealt with are becoming more clearly defined. One of these problems is that of the training necessary to fit the younger men to carry on the growing work before them; and the rapid growth of the industry makes the problem of more than usual importance.

In any industry the men employed may be divided into three main groups: the general body of employees, the executive officials and the administrative officials. The ideal system of training is one which, whilst establishing a regular curriculum for each class of worker, allows sufficient latitude to permit the advancement of men whose ability and character show them deserving of transfer to higher positions, even though the regular course of training has not been followed.

The problem is not a new one, and the most successful solutions appear to be those which are flexible enough to meet the steadily changing conditions that arise. My own view of the most suitable general training of the officials is that it should include not only technical

instruction and practical experience in the supply industry, but also experience in one or more sections of the manufacturing industry. A system of interchange between manufacturers and supply undertakings should be of value to both sections of the industry, and in many cases benefit would, I think, arise by periodical interchanges of staff between supply undertakings. In this connection my view is that such a course of training should include not only the technical but also the accountancy side of the business. Familiarity with the ordinary methods of accountancy is somehow quite unusual in young engineers whose mathematical abilities go far beyond the simple but important arithmetical processes of the bookkeeper.

The whole subject is one which, I think, should repay discussion, bearing in mind that although the system of scholarships at universities and technical schools helps to keep open the career to the talents, there is a direct obligation on the industry to bear the cost of post-graduate training by providing salaries for those young men who show the necessary ability and energy which are sufficient to encourage them to continue this widening of experience beyond the normal period of their training. Were such a system generally adopted, I believe that the industry would benefit largely.

Progress.

The progress of the electricity supply industry throughout the world during the past 20 years has been so rapid and the developments so numerous that it has almost seemed that no anticipation of its future possibilities could be exaggerated, and, as a consequence, there have been (and are being) made claims for the use of electricity which exceed the present probability of fulfilment. This tendency to overstate the case is likely to be harmful in producing a natural reflex of disappointment when the facts are known. Already we find in various quarters that the developments in this country are compared detrimentally with those made in other countries, without any account being taken of the conditions which would explain the difference. As a consequence, notwithstanding that developments are being made and conceived on a larger and more ambitious scale than ever before, there is further talk of legislative amendments for the purpose of stimulating progress.

The lines which development is following in all parts of the world have been indicated and established principally by British engineers, and there is no evidence that the ability of our engineers in any way falls below that of engineers of other countries. This being so, it savours of the ironic that the electricity supply industry in this country should have become so much the sport of theorists and the victim of legislative experiments.

The development of electricity supply in any country depends on the particular circumstances attending production and use, and comparisons between different countries without considering these circumstances are likely to be, not only valueless, but misleading.

Electricity supply has a great future, but it is not a panacea for industrial and social ills, and it behoves engineers to speak out just as definitely when unjustifiable claims are made for it as when it is unfairly attacked.

The development of the use of electricity is largely due to considerations of convenience in meeting the desired needs of civilized communities. Its development is limited by a consideration of cost in relation to the cost of other means of supplying the same needs. The degree to which convenience can be translated into terms of cost is a measure of the necessity or of the standard of luxury of the community. For example, regarding electricity merely as a means of providing in a convenient form sound, light, power or heat, we see that for signalling or sound-recording at a distance electricity is without a competitor; the consideration of cost for this purpose is confined to that of alternative electrical methods.

Lighting.

For lighting, the convenience, cleanliness, safety and comfort of electrical methods place them in a most favoured position relatively to other illuminants; but the development of electric lighting—limited in the past by the cost of production and at present by other conditions, to which I shall refer later—has been made in competition with gas and oil and has had, in many cases, to oust the older method.

One of the most notable achievements of electrical engineering has been the reduction in the cost of electric light in the present century, by increasing the illumination six-fold for the same amount of electricity. To-day, electricity is the cheapest form of illuminant, and, as a consequence, its use for lighting purposes is growing at a rate never before equalled in the history of the industry.

It is of interest to consider what are the limitations to further use and what is the probable development.

No general statistics are available of the number of dwelling-houses using electric light, but probably less than 20 per cent of the houses in this country are wired and connected to the public supply. This small proportion is due, I think, to considerations other than the cost of producing electricity, the first being the cost of the consumer's installation.

In existing houses, many of which are already supplied with gas, the introduction of electricity involves the expenditure of capital on wiring which, under present conditions, the landlord is not prepared to provide, on account of the Rent Restriction Acts, and the tenant is reluctant to expend on an improvement which may result in an increased rent when restrictions are removed. Assuming that this difficulty can be overcome by arrangement between the landlord, the tenant and the supply undertaking, a considerable addition to the number of consumers may be anticipated.

A second consideration is that in the natural order of development those houses which could be most cheaply supplied have been dealt with first, and the supply to the others, for various reasons, will involve a proportionately greater cost of distribution.

The 1921 census enumerated for the first time the number of rooms in dwellings of various kinds, including flats and those occupied business premises in which the portion used for domestic purposes is not less than three-quarters of the whole. The figures are not yet completed for the whole country, but a consideration

of typical districts is of interest as indicating the possible demand if the whole of the houses were lighted electrically. I have taken as an example the census figures for London, Manchester and the West Riding, and find the following division as to size :—

Census of Dwelling-houses.

	Percentage of total number of houses where number of rooms per house is:			
	1 to 3	4 to 5	6 to 8	9 and more
	per cent	per cent	per cent	per cent
London.. ..	18	27·1	42·4	12·5
Manchester ..	11·8	65·8	20	2·4
West Riding of York.. ..	33·8	48·3	15·5	2·4

It may be assumed, I think, that the majority of existing consumers dwell in houses of 6 or more rooms, and that the untouched field lies principally in the supply to the smaller houses. The extent to which this field varies will be seen in the various districts. In London 45 per cent, in Manchester 77 per cent, and in the West Riding 82 per cent of the houses are of this smaller size. Not only are the dwellers in these smaller houses potentially smaller users of electricity, but the cost of distribution per house is practically as high as for the larger users. It follows that on the one hand the reduction of the cost of distribution is of the utmost importance, and the stimulation of the use of electricity for domestic purposes other than lighting equally so on the other. Here it may be said that the general standard of illumination in dwelling-houses in this country is low, though much above that of 20 years ago. The public have not yet realized the decorative possibilities of electric light, and the unshaded filament—an abomination in the sight of any thoughtful person—is still too frequently seen. We may, however, assume that the tendency to soften and diffuse the light and to harmonize the system with the general decoration of the room will continue to grow, with a consequent increase of consumption in the larger houses.

To use a popular though often untrustworthy basis of comparison, the present-day consumption per head of population for lighting purposes in this country is about 10 units per head, representing a supply to some 20 per cent of the houses. The complete supply should produce figures of 40 to 60 units per head, depending on the proportion of large houses. It should be emphasized that this question is not primarily one of generation but is almost entirely determined by two considerations, the cost of wiring the houses and the cost of distributing the electricity.

Power.

While the cost of electricity for lighting is primarily determined by the cost of distribution, in the case of power supply the cost of generation is the principal part.

The early development of power supply was largely aided by the advantages of subdivided electrical driving by a number of motors, in place of the general method of using line shafting, countershafting and belts driven from a main engine in factories, or small non-condensing engines in large premises such as shipyards. Once the power user purchased electricity and adopted the electrical driving of machinery he was in a position, for the first time, to measure accurately the amount of power required for each machine and to base his future plans on accurate data.

The continued development of the use of the public supply has been maintained only by a continued reduction of the cost as compared with that of individual generation, and the margin has at times been small. The growth of the industry has, however, now reached such a stage of development that the advantages of centralization permit in the majority of cases the supply of electricity at prices which show a definite saving of cost to the user, in addition to the less direct, but important, advantages of convenience. Generally speaking, the possibility of supplying a power user at a price lower than his own cost of production depends on the magnitude of the power plant relative to the central system.

To-day the principal industrial areas of the country are being supplied from stations of from 50 000 to 100 000 kW. Further economies will accrue from the growth and interconnection of these stations and the complete supersession of small stations in industrial areas—a work which is steadily progressing.

Apart from the economies of capital and operating costs inherent in large generating stations, the accumulated experience of the specialists who now control the operation of these stations produces economies in working not otherwise obtainable, and I am confident that we are entering on a new phase in the industry and that the days of the individual industrial plant are numbered. Certain special cases must, however, be regarded; those, for example, in which a large use is made of steam for manufacturing processes and those in which the steam engine on account of its special characteristics is still regarded as more suitable to the work.

A careful study of works using both motive power and steam for process work shows that in many cases the advantages of combining the power plant and the steam-raising plant are illusory and that economies will result from the separation of the two. Accurate records of analysis of industrial operations of this nature are scarce and the industry would be helped by further research of an unbiased nature.

The second case is perhaps best evidenced by the colliery winding-engine, the retention of which is in many cases more a matter of prejudice in favour of a well-tried machine than due to the consideration of the cost of installation of the electrical equipment. A partial solution of the winding-engine problem which has found a considerable amount of favour has been the use of the mixed-pressure turbine in conjunction with the winding engine. The method is falling out of favour because in most cases it perpetuates wasteful machinery and only reduces the waste. Modern centralized production shows, over the partial method, an advantage which is becoming greater as the scale of production increases. In the past, moreover, a public

supply on a sufficiently large scale was rarely available and the special devices necessary to reduce the peak loads were costly. To-day, in all the principal coal fields a public supply is available on a scale which no longer need be concerned with the variations of load, and the simplest type of motor may be fitted and supplied from the general system without difficulty.

The satisfactory experience of electric winding for collieries gives every assurance of a further and rapid extension of use.

Heating.

The use of electricity for heating must take into account the particular requirements and the method of application before it can be said that it is the most suitable or most economical method to be adopted.

The relative price of a heat unit in the form of coal and in the form of electricity—unfavourable as the comparison is to the latter—is, of course, not the criterion of its value unless the efficiency of utilization is taken into account. When this is done it is found that for many purposes electric heating is suitable and economical. For some, its cost is prohibitive.

The adoption of electricity for general heating purposes, apart from special applications to which it is suited, is not probable until substantial and vital changes are made in the methods of production, and the supply-engineer's thoughts must therefore be directed to the most suitable combination of means of heating, lighting and power supply in dwelling-houses and factories.

This consideration leads to the further one of the measure of co-operation which should be established between suppliers of coke, gas or other fuel, and those of electricity, in the best interests of the public. The subject of coal distillation is therefore one of particular interest to the electrical engineer.

Coal.

The principal condition affecting the development of electricity supply in any country is the price of coal. The advantages of centralized power production from coal lie in the better utilization of capital and in the more economical use of coal due to design, skilled operation and diversity of demand.

It is obvious that in a country where coal is dear the advantages of centralization of power production are greater than in a country such as our own where coal has been cheap. As a consequence, the development of electricity supply in countries where water power is available and where coal is dear has been much more rapid than in this country, not, it will be noted, necessarily due to a spirit of greater enterprise, but primarily because it was the best or only economic solution of the power problem.

In the early days of power supply the industry gained a temporary advantage over the generality of power users by their adoption of mechanical grates and the use of small coal, the price of which was low on a heat-value basis. The cost of small coal, however, has gradually risen so that its market price to-day is more in accordance with its heat value, and the supply-engineer's advantage is almost wholly in his more economical methods of use. It is important therefore to consider whether, by the adoption of other methods, the industry can place itself in a position of still greater advantage over the ordinary user, and in this connection the striking world-wide changes which are going on in the demands for fuel must be regarded.

The utilization of water power and the steadily increasing efficiency of power production from coal indicate that the existing demands for mechanical power will be met by a rapidly decreasing consumption of coal. In our own country the pre-war consumption of nearly 200 million tons of coal a year represented a use in many respects wasteful, and the engineering progress of the last 10 years has already made a substantial reduction. The growing use of oil fuel is also in a large measure in substitution for coal.

These considerations tend to reduce the world demand for coal and, were they not qualified by the increasing demand for power, the prospect before coal-producing countries such as our own would be one of unqualified gloom. Whether, or for how long, this country can continue to export large quantities of raw coal seems therefore not so much a question of national resources as one of price and demand.

The most efficient use of coal for power production is measured by the coal consumption per unit of electricity, and with the materials and methods to our hands electrical engineers are rapidly approaching the maximum of economy. On broader grounds it may be considered whether the quantity of coal consumed is the true criterion or whether a process which, whilst consuming more coal, yet produces a greater profit per ton is not to be preferred.

The demands for oil fuel, for light spirits and for artificial fertilizers, all of which can be produced by the distillation of coal, should, if possible, be met by home products; and the distillation processes should, so far as is economical, be carried on in combination with the production of electricity. Coal distillation is a subject which the electrical engineer must regard as within his province and it may be of interest to enumerate some considerations which I think will engage his attention.

There are in commercial use two classes of coal-distillation processes: coking processes, and regulated combustion or producer process. The coking processes are the more important and include those in use by the gas industry and by the coke-oven industry; the producer processes which result in complete distillation of the carbonaceous matter and its conversion to gas are of less importance.

The success of established processes depends on an appreciated or increased value of certain products above their absolute fuel value, due to the existence of a demand for potential energy in a particular form. This increase of value is not obtained if all the fuel products are used for power production, unless the form in which they are obtained—for example, gas or oil—permits the use of more efficient generating plant or, due to the ease of control, results in a more efficient process of generation. If, therefore, a coal distillation plant is worked in conjunction with the production of electricity, commercial success calls for the marketing of the products (such as oil and ammonia) which are not used for the primary business of producing electricity.

The processes at present in use involve the treatment of a much larger quantity of coal than would be required for direct combustion, and the disposal of products the total value of which exceeds that of the coal required for direct combustion. The selling price of these products depends on world-wide competition with products obtained from other sources than coal. In other words, if such a process were adopted primarily for the reduction of the cost of electricity, its success would depend on conditions which make, or may make, the revenue from the sale of fuel to the electricity works a minor matter.

It may be said, therefore, that the adoption of any established commercial process of distillation would introduce into the electricity supply business an element of speculation which is foreign to the industry as it exists to-day, and which might alter substantially the nature of the industry and the security which it at present offers to the investor.

The cost of distribution is so considerable a charge for many uses that cheap electricity depends very largely indeed on the ability of the undertaking to raise capital at a low rate. A low rate of interest or dividends on capital is only consistent with the present faith of the public in the stability and security of the industry; consequently, any speculative element not controlled by the observance of engineering and commercial principles peculiar to the industry might lessen public confidence and make the cost of electricity greater.

Keeping this in mind, it follows that the most suitable process is one in which the quantity and nature of the by-products can be varied most readily to meet changing markets, and one that should be commercially justifiable even when a large proportion of the products is used in the production of electricity. No existing process can be said by the experience of working on a commercial scale to be demonstrated as worthy of adoption principally because of the heat losses in the process, the capital outlay involved and the operating expenses.

The quantity of heat required for the distillation of coal as ascertained by laboratory tests is small, of the order of 2 or 3 per cent, but, in practice, heat losses are considerable. The development of continuous processes and shorter times of distillation seems essential to cheap production.

The utilization of gas from distillation processes is another interesting aspect of the problem. Gas fuel for steam-raising has, from my own experience, proved eminently satisfactory over a period of years; but the special value of gas for distribution offers a market of higher prices, and coal gas such as produced from coke ovens is finding more and more outlet in sale to gas undertakings.

Research is also proceeding for the production of oils from coal by chemical reactions not consequent on distillation, and the progress made suggests many interesting possibilities which may have an important effect on the practice of power engineers.

Generation.

The design and operation of electricity stations, whilst showing progressive development, has undergone no startling changes since the introduction of the steam turbine and, so far as the thermal efficiency of the present type of plant is concerned, we are steadily approaching the limits.

The process of conversion of the heat energy of coal to electricity takes place in three steps: the conversion to steam, from steam to mechanical power, and from mechanical power to electricity. Of the apparatus used as designed for present-day practice the boiler may have an efficiency of 85 per cent, the steam turbine an efficiency ratio of 87 per cent, and the alternator an efficiency of 97 per cent, or an overall figure of 72 per cent.

The serious consideration in this not unsatisfactory ratio is of course that the heat cycle used as a measure of the turbine efficiency-ratio has an absolute efficiency of a low degree, and if we take the real overall efficiency of the best modern station under working conditions we find that it rarely exceeds 20 per cent. This is practically double the efficiency of 20 years ago, during which time the pit price of coal has also practically doubled. In effect, therefore, the engineers responsible for these developments have, by their efforts, discounted in full the increased cost of coal—no mean performance.

It is of interest to consider the possibilities of development in the efficiency of the heat cycle. Improvements can be made by reheating the steam or by the progressive heating of feed water, but the degree of improvement is not large.

The more important possibility is that of increasing the temperature and pressure of the steam. The combustion of coal under properly controlled conditions is such that a flame temperature of several thousand degrees may be attained, and, could steam be produced and utilized at such a temperature on the present heat cycle of operations, a substantial increase of thermal efficiency would be possible. The practical limitations to-day are the nature of the materials used and the design of the apparatus, the latter a minor consideration if suitable materials were available.

The progress of the past 20 years has been a step-by-step improvement in design, construction and methods of operation, and the field for further improvement by a continuation of this work, though not large, is one of considerable promise. It must, however, be borne in mind that the total cost of production includes not only that of fuel but also the cost of providing, operating, and maintaining the plant. It may be assumed that these costs are, in a principal station, divided in the proportion: coal 50 per cent, capital charges 30 per cent, operating costs 20 per cent; from which their relative importance may be judged.

In the total cost of electricity the cost of capital is an item which is second in importance only to that of fuel. The reduction of the capital cost per kilowatt of plant may come about by the adoption of larger units of plant and by the development of design to obtain a greater output of electricity from the same use of material. The size of the generating unit is limited by a consideration of capital investment in spare plant and by a consideration of the load on the station at night times and week-ends. As the demand for electricity increases, the justification for larger units also grows and the cost per kilowatt should fall.

As to the more economical utilization of materials so

as to obtain a greater output from the capital investment, there seems considerable room for improvement. For example, in the steam boiler an average evaporation of 6 lb. of water per square foot of heating surface is a poor utilization of materials when we know that under certain conditions an average of 20 lb. may be obtained.

The consideration of boiler design in relation to heat transfer is a subject of great interest. The transfer of heat from a radiant surface proceeds so much more rapidly than the transfer from the hot gases by conduction, that there has been a natural development of the volume of combustion chambers and a more careful consideration of the amount of surface exposed to radiant heat.

The design of the furnace is limited by the available refractory materials, on which subject kindred scientific institutions have done valuable work. In this direction, interesting developments have taken place in the production of new and more refractory materials and in the design of the boilers and furnaces to reduce the amount of refractory material required.

Reviewing the developments which have been made, it appears that progress has been on right lines and has resulted in reducing substantially the cost of generating electricity. The direction which future developments should take seems clearly indicated and should result in further economies, but not of a revolutionary amount.

Distribution.

So much has been said in the Press about the reduction in the cost of producing electricity that the ordinary consumer of electricity for lighting may be excused for wondering why the price of electricity is so high. The answer is, of course, that the cost of distribution to small users whose use is only intermittent, as is the case with the user of electric light, is governed almost entirely by the cost of distributing mains and apparatus, and if by some means the fuel bill were halved the effect on the price of light would be but trifling.

It may be taken that the cost of distribution for lighting adds some 300 per cent to the cost of production; and it is of interest to note by way of comparison that the distribution of milk, also sold from house to house in small quantities, adds only 100 per cent to the wholesale price. The cost of distributing electricity requires our most careful consideration, more particularly as one finds that the methods adopted differ but little from those of 20 years ago. I believe that a frank interchange of views between supply engineers on these methods would be of great value.

The other line of development, namely, the reduction of the average price by encouraging an increased user of electricity, will naturally not be overlooked, and it is gratifying to find that the work of those engineers who have devoted their energies principally to the development of domestic uses such as cooking is beginning to bear good fruit.

The problem of supply to the small householder, already referred to, and of supply in rural districts with scattered population, is one in which the costs should be examined with particular care so that the supply to these users shall not prove a burden on the undertaking. It is rather generally assumed that the supply undertakers should charge one price for the same service in any part of their area. In a densely populated town this may be justifiable, but the acceptance of the principle for rural districts will result either in penalizing the town dweller or in financial loss on the rural supply.

Tariffs.

The subject of tariffs is of importance in that a greater measure of public goodwill is likely to be obtained by a proper understanding by the consumer of the underlying principles which determine the charges for each particular class of electrical service. The principles are, of course, the common economic principles applicable to the production and distribution of any commodity and are not peculiar except in degree to electrical service.

A closer analysis of costs of each operation not only is of value in determining the possible selling price, but is in the interests of the consumers individually and as a body. The development of an undertaking requires a margin of profit available for fostering new extensions of the system or new applications of use, for research and for advertisement. It is obvious that any arbitrary ruling, such as, for example, that prices shall be determined by cost plus a fixed margin, would prevent the necessary accumulation of a development fund in its widest sense.

The cost of electricity at the station busbars may be expressed with reasonable accuracy in the form of a charge per kilowatt of demand plus a charge per unit; the average cost at main distribution centres may be expressed in the same form, but to express the cost delivered to consumers of different classes we must adopt a division into three parts, which may be expressed approximately as :—

(1) The fixed charges on generation.
(2) The running charges per unit.
(3) The standing charges on distribution.

The principle of averaging these distribution charges has been accepted in the past without question as a sound one, but it is at least questionable whether development is not hampered by this method of selling, for the effect is to penalize the profitable consumer to enable others less profitable to be served. It would, in my view, be unsound to develop undertakings beyond the economic limit, either by penalizing existing consumers or by State aid, in that alternative services exist for most needs, e.g. lighting by gas, power by self-contained plants such as the petrol engine, the oil engine and the steam turbine, heat by gas or coal, and so on.

I believe that there is a very wide field for the further development of electricity supply for all purposes, but I deprecate unprofitable development either at the expense of existing users or the public as a whole.

Interconnection.

The development of the industry commencing by generation on a small scale at separate centres is, by a natural process, now reaching a stage where for various reasons the limit of aggregation of generating plant in a station may be foreseen. As a consequence, the generation of electricity to supply

any considerable area will be carried on at more than one centre.

There are economic advantages in the interconnection of the systems supplied by individual stations, within limits not difficult to decide, the extent to which the interconnection may be justifiably carried being determined by the balance of advantages and disadvantages in any particular case. The advantages are: a reduction in the amount of spare plant, or greater security; more economical loading of plant and greater diversity of demand; the possibility of extensions by larger and more economical steps; and the reduction of capital invested, per kilowatt of plant. In water-power schemes the diversity of water-flow in different watersheds and the pooling of water storage are additional advantages. The disadvantages are principally the capital cost of interconnection and the consequent annual charges for capital and operation.

The economical extent to which interconnection may be carried is largely a matter of the working pressure and amount of energy to be supplied. The limit of working pressure is determined by the system of transmission adopted. It has been assumed in this country that underground mains are essential for this purpose, though in other European countries overhead lines are being generally used. In this connection the pioneer work of the British cable makers is notable, and the prospects of three-core cables at pressures up to 60 000 volts are stated to be favourable.

The use of three-phase alternating current has by general consent proved the most economical of the available methods of transmission at high pressures. In the past, local generation and distribution have been carried out at pressures of 6 600 and 11 000 volts with reliability and, compared with other systems, a saving of cost. Where the systems in a large region are to be interconnected the need arises for higher pressures, and we are now confronted with a new set of problems appertaining to this wide interconnection.

The arguments for interconnection are well known and, due to the undue prominence given to them, the disadvantages of our present methods have been correspondingly placed in the background. Let us consider what are these disadvantages. The first one, inherent in the three-phase alternating-current system, is that the cost of switchgear and protective devices increases rapidly with the size of the supply system. This must be so, when we consider that the switch must be designed not merely to cut off a faulty section of the system but also to stop the flow of power from the system as a whole into the faulty section.

The duty of a switch may be reduced by the introduction at suitable places of additional reactance in the apparatus used. The alternator once designed with the object of maintaining constant pressure is now preferred to have a contrary characteristic; the transformer also is designed to withstand fault currents at the expense of regulation and, in addition to the power current in the system, large magnetizing or idle currents exist and must be controlled. As a consequence, the regulation of pressure at the various main distribution centres and at important sub-centres requires the introduction and use of regulating apparatus, involving further expenditure of capital and increased cost of operation. In this respect the art has not progressed as rapidly as the need.

Fruitful lines of research are the better understanding of the duty and behaviour of oil switches, a work which is being undertaken by the Electrical Research Association, and the possibility of reducing the duty of the switch without unduly affecting pressure conditions. The use of reactors is but a palliative. A switch opening under fault conditions has to deal with the stored energy in the system, its operation is so controlled that the flow of energy into the fault has already grown to a considerable magnitude before the switch opens, and its design is such that if it opened when the fault current was a maximum it would probably prove ineffective, the time delay in opening permitting the absorption of the energy, though usually destructively, in other places than the switch.

The development of electronic valves has introduced a device which is free from friction and from time-lag of operation such as is caused by electrical induction or mechanical inertia. Their application to the control and regulation of electricity supply systems is a promising prospect. If control can anticipate the disturbance caused by a fault, instead of as at present being consequent on it, a great advance will obviously be made.

Another line of research is the application of direct-current transmission, a work with which the name of one of my predecessors in the Presidential Chair, Mr. J. S. Highfield, is closely associated. The reversion to direct current would bring with it many advantages, and one looks forward with interest to the outcome of the work being done.

It is of interest to remember that early systems of supply were developed which were regulated by a variation of pressure from zero to a maximum. Practice of the last 20 years has been almost wholly on the lines of constant pressure, both of steam and of electricity.

The problem of insulation is also a serious one and the three-phase system, though the best available at the present time, cannot be regarded as even approaching the ideal.

High pressures are necessary to enable the concentration of generation and the transmission of electricity over long distances and, this being so, one of the most urgent problems for solution is that of providing a means of transmission at high pressures which is free from the disadvantages of the present system and, in particular, is less costly to install. For example, the carriage of coal from, say, South Wales to London for the purpose of generating electricity at stations in London is more economical than the establishment of generating stations in the coalfield and the transmission of electricity from the coalfield to the metropolis. So long as this is the case it is idle to assume that because in certain countries where water power is used a transmission for 1 000 or even 500 miles is justified, a similar provision would be justified in this country. The solution of this problem is one that it is hoped is not far distant.

Overhead lines are in certain circumstances a means of economy, but in a densely populated country difficulties are met with which in many cases make their use

of doubtful economy. The legislation of the Electricity Supply Acts of 1919 and 1922 have given the suppliers of electricity in this country most valuable powers with regard to overhead lines and it is of interest to see the steady, though slow, increase in the use of such lines. There is still a considerable amount of prejudice to be met and also quite legitimate criticism from those whose amenities are disturbed. A general discussion of these matters, a fuller presentation of the case to the public, and a concerted effort to obtain the most economical design consistent with safety should be of general benefit.

Legislation.

And now, as a somewhat harassed industry is threatened with more legislation, a word as to the legislation of the past.

The first Electric Lighting Act of 1882 contemplated parochial systems of supply with either immediate or ultimate operation by the local authorities individually. This was, as experience has shown, a basic error.

The Power Company Bills at the beginning of the century were framed on broader lines, but, Parliament halting between two opinions, the Acts were so emasculated for the protection of existing undertakings that their value was much reduced.

In the last 5 years we have had two new general Acts which endeavoured to reconcile the conflicting ideas of municipal working and private enterprise under the guidance of a body of Commissioners who were given the task of acting as judges and advocates at the same time.

We are said to be a nation whose genius is compromise; and the national trait, with a good deal of discussion and a considerable and consequential amount of delay, seems to be asserting itself beneficially so that progress, disturbed as it was by the new ideas, is resuming its way. For the work done by the Commissioners in the most difficult circumstances, I believe that the whole industry has a great admiration, but it is to be hoped, for the sake of the industry and the country it serves, that an opportunity will be given to those engaged in it to show what can be done without further legislative interference.

The progress of the industry even in a time of national trade depression is rapid, the technical and commercial difficulties are being overcome and there is, in my view, every prospect of continued development on sound commercial lines if, as in the past, each step stands the test of justification by results. Electricity supply is a beneficial and useful service to the community, but it is unwise and misleading to suggest that its artificial stimulus will prove a solution for all industrial ills. The national need for economy was never more urgent than it is to-day, and I am confident that electrical engineers, with other workers in the field of applied science, will, if permitted to proceed on commercial lines, subject to reasonable control in the public interest, make progress in the next 20 years to a degree even more notable than that of the past 20 years, during which I have seen electric power supply grow from a small and experimental venture to its present importance.

The co-ordination of individual solutions of the problems to our hand is more likely to lead to success than the imposition of a method of production and control which, however decided to-day, must, by the progress of science, be challenged and modified to-morrow. The great progress of engineering goes on at a snowball rate; every extension of the boundaries of knowledge touches a wider field of the unknown and, as surely as one may venture to prophesy anything, it may be said that the practice of a decade hence will differ substantially from that of the present time.

Those of us who have been engaged in the development of electricity supply remember the serious opposition of municipalities who, as owners of gas-works, feared the competition of the new illuminant. History records that the gas engineers experienced in their time the organized opposition of the candle makers.

The very fact of the existence of so large a body of trained engineers as is contained in the membership of the Institution is an assurance of change. Let us hope that when the time comes for our present practice to be met by a new competitor in public service, progress will be permitted to take place on an economic basis and that it will not be hampered because public funds invested in the industry will be jeopardized by the new development.

The industry, like all other human organizations, is changing and must change if progress is made. The changes will be brought about largely by the abilities and inventive powers of engineers, and I feel that it is particularly important that our younger members should not be overawed by the magnitude of the work done in the past but should preserve that spirit of adventurous research which the pioneers of the past possessed in so great a degree.

WESTERN CENTRE: CHAIRMAN'S ADDRESS

By W. NAIRN, Member.

(Address delivered at BRISTOL, *6th October,* 1924.)

In this address I propose to deal principally with the work which lies at my hand—the applications of electricity to the lighter forms of transport.

HISTORICAL.

The earliest application of electricity to the movement of passenger vehicles in this country took place in 1883 and 1884—40 years ago—when electrified lines were laid at Giant's Causeway, Brighton, Blackpool, and Bessbrook-Newry, the promoters being Messrs. Traill, Magnus Volk, Holroyd Smith, and Mather and Platt respectively. Little interest was taken in these lines, but they gave a practical start to the experimental work which was carried on until in 1890 the American companies succeeded in placing on the market single-reduction motors which were so reliable that the doom of the horse for tramways was sounded.

By 1890 the rush to electrify was in full swing in America, but it was not until five years later that a real start was made in this country with the construction of electric tramways as we now know them. In Bristol the line from St. George to Old Market-street was amongst the first, having been built in 1895.

For the original equipments, we in this country were indebted to the experiences gained in the preceding five years in America, and the early struggles of American engineers with open-type motors of 7 h.p. or 8 h.p. were practically unknown to British engineers. The greatest praise that can be given to these early equipments imported from America is that most of them are running to-day and comparatively little improvement on them can be suggested. These motors were rated at 25 h.p. and there were two to each car. Where the weight of the car is increased by adding vestibules and top covers the size for new equipments is about 35 h.p., although the London County Council for their heavy cars and high speeds have recently adopted motors of 63 h.p. The distinction between the old and the new motors is that the latter are fitted with interpoles and are ventilated, bringing the weight per h.p. down from 80 to 40 lb.

The application of roller and ball bearings to electric rolling stock was tried in the early days with little success owing to the frequent breakages. Within recent years, however, further experiments have been made and, owing to the improved materials available and also to improved methods of construction and testing, these bearings now stand well up to their work. The object in using roller and ball bearings is two-fold; first the saving in power, and secondly reduced maintenance charges.

In Bristol three cars were equipped with ball and roller bearings in armatures and car axles, and exhaustive tests were carried out on them to determine the saving in power that might be expected. One of the first points noticed in these tests was that the percentage saving was much greater on level routes than on hilly routes. This is due to two factors. In descending hills with the brakes applied no saving in power takes place, whilst in ascending hills the ratio of the friction current to the total current is small and any saving in friction current results in a small percentage saving. Due to the difference in gradients and also to the number of stops on different systems, there is a wide variation in the results obtained in different towns, but in Bristol the saving in power on hilly routes was found to be 6 per cent and on the level routes 11 per cent. These results call attention to the difference between roller bearings in a workshop shaft and roller bearings on a street car. In the former money is being saved all the time, whereas in the latter there are many periods when the roller or ball bearing is a distinct disadvantage, viz. when descending hills and when accelerating.

Regarding brakes, the earliest cars were fitted with cast-iron shoes acting on the wheels and applied by hand power. This was the service brake, and an emergency brake was provided by short-circuiting the motors when they were acting as generators. This latter brake did no good to the motors and was not agreeable to the passengers; it was therefore replaced by the rheostatic brake, the motors when generating being connected through a resistance which could be varied from the controller. The next step to the rheostatic brake was the magnetic brake acting on the rail, the magnet being energized from the motor current, and the track shoe was sometimes coupled to the set of wheel brakes so that the drag of the magnetic shoe applied them also. In the Edinburgh system—the most modern of our tramway systems, having been equipped only in 1923—the magnetic track brake is used. This acts only on the rails, but is also capable of being applied by compressed air. The compressed air is obtained from an electrically driven compressor installed on the car and driven from the trolley wire.

REGENERATIVE CONTROL.

The question of regenerative control on street tramcars has always been an attractive one to electrical engineers because the electric vehicle is the only vehicle in common use to-day which is reversible. A steam locomotive going down hill cannot return coals to the tender, nor can a petrol vehicle under similar circumstances refill its petrol tank, but it is quite possible for an electric vehicle to return electricity to the line or to

a battery. Unfortunately, regenerative control has not been a commercial success, due to the fact that the saving in power did not pay for the capital and maintenance charges of the regenerative equipment. The Raworth regenerative system made the most headway in this country. In this a shunt-wound motor took the place of the series motor and the driver was given control of the field. One result of this was a tendency for the driver to "race" the car on a weak field, with a consequent rise in current consumption, so that when the regenerated units were subtracted from the used units there was little difference between this figure and the units used by the series motor car. In Bristol four cars were equipped with regenerative control, the results of tests showing a saving in power of less than 3 per cent. With the further cheapening of the cost of electricity the future for regenerative control on either trams or railways is not very bright; I make this statement whilst being fully alive to the fact that in America the latest railway electrification schemes are all equipped for regeneration, even where current is generated from water power. The gradients in that country are, however, very different from those prevailing in England, and regeneration is used more for the purpose of avoiding the wear and tear due to braking than for the saving of power. On the Chicago, Milwaukee and St. Paul Railway there is one run of 200 miles down the side of the Rocky Mountains.

Types of System.

Apart from storage battery cars, the earliest means of applying electricity to street cars was either from an overhead wire using the track as the return, or from a conduit in the track with two insulated conductors. Subsequently a system known as the surface contact system was tried in a few towns. The use of overhead wires is now universal, the exception being the London County Council conduit system. British practice in overhead lines followed the American, except that the lines were built more substantially and were more sightly. Few changes of moment have taken place. Hard-drawn copper is still the most popular conductor but, where the car services are heavy, alloy conductors are used, although their conductivity is as low as 40 per cent of Matthiessen's standard. A new conductor which promises well is a cadmium-copper alloy which combines a conductivity of over 90 per cent of Matthiessen's standard with wearing qualities approaching those of the other alloys. For insulation purposes porcelain is gradually replacing the composition insulations introduced from America. The design of the various wire fittings has been considered recently by a committee appointed by the Municipal Tramways Association. This committee has standardized a complete line of fittings, and a standing committee has been appointed to consider suggested improvements. It is of interest to know that this committee was brought into existence on the suggestion of one of the members of this Centre, Mr. H. I. Rogers.

Electrolysis.

A subject which gave rise to a good deal of discussion in the early days of overhead lines was electrolysis. Here, again, the experiences of American engineers were helpful to us as the first American rails were unbonded and the difference of potential between rails and water pipes often exceeded 20 volts, so that a great deal of experience was gained in a very short time. In fact, the early depredations caused such alarm that one writer of the period foretold that the extensive pipe plants of the gas and water works were doomed to immediate disintegration, with the inevitable result that the unfortunate inhabitants of the cities would be drowned if they were not previously blown up. To safeguard the public the British Board of Trade—which was then responsible for transport problems—framed the regulations which, among other provisions, limited the voltage between rails and pipes to the voltage of one Leclanché cell when the pipe was positive and three Leclanché cells when the pipe was negative. Further, it put on the tramway undertaking the onus of building the tramway so that it was electrically separate from the pipes of other undertakings, but unfortunately there was no similar obligation on authorities laying pipes subsequent to the construction of the tramway, so that this desirable provision was rendered void. The greatest credit is due to those who originally framed the regulations for their masterly handling of what was then a new study, and as a result of their labours the existence of electrolytic action is unknown to the general public. Before the advent of electric tramways or electrical undertakings lead pipes suffered from corrosion in certain soils, and it is to-day a matter of great difficulty to determine whether corrosion is due to electrolytic or chemical action.

Permanent Way.

As regards the permanent way, electricity has come to its aid and the overhead wires provide power for driving concrete mixers, compressors for operating pneumatic picks, rail grinders and—perhaps the most useful of all—the electric welder for welding the fish-plates to the rails instead of bolting them, and also for filling in spooned or hammered joints. Both the carbon arc and the metallic arc welders are used and give good results.

Types of Vehicle.

For rural transport, development in this area has been by petrol omnibus, but in many districts in the Midlands the railless vehicle with two overhead wires is making headway, and has proved itself a practical form of road passenger vehicle using the cheapest power available—electricity. The storage battery vehicle has not made the progress which was expected; this is due not to any inherent engineering defect in the vehicle but to its high first cost and lack of charging facilities. Even where a supply of electricity is available, the price of a motor-generator and switchboard has to be added to the cost of the vehicle, making the price of a single vehicle prohibitive as compared with that of a petrol vehicle. In its proper sphere the storage battery vehicle has no equal; this sphere is where large fleets of vehicles are required, stops are frequent and long mileages per day are not required. The maintenance charges are low, it is silent and clean, and no fire risk attaches to it.

It is unfortunate that prices cannot be brought down to a competitive figure. As a truck for indoor use it is an unqualified success and has no competitor.

Between the purely electric vehicle and the petrol omnibus, there are two distinct types of petrol-electric vehicles. In one the whole power of the engine is converted into electricity which drives a motor or motors connected to the rear wheels. This is the arrangement of the Tilling-Stevens omnibus. In the second system, known as the Entz magnetic system, two d.c. machines are employed. One has its field connected to the engine and its armature to the propeller shaft. The second machine has its field connected to the car frame and its armature to the propeller shaft. The first machine is called the clutch generator and the second machine the motor. On top speed the clutch generator is used as a clutch alone when it is short-circuited on itself; on speeds other than top speed the clutch acts as a generator and supplies power to the motor. Both systems give the advantage of smooth speed control with the elimination of gear-box and clutch, two items of petrol vehicle equipment which are makeshift devices.

On the Tees-side a hybrid vehicle is in use. It is a petrol-electric vehicle wound for 500 volts and fitted in addition with two trolley poles for running as a trackless vehicle where overhead wires exist.

Electric Lighting and Ignition.

Passing to the purely petrol vehicle, the equipment of interest to us is the electric lighting, and starting and ignition outfits. No passenger car is fully equipped without a lighting and starting set, but the starting set is still omitted from most of the heavy petrol vehicles engaged on omnibus or commercial work. It is a curious fact that the development of these sets has been carried out not by the recognized electrical engineering firms of the country but mostly by those who in the past were makers of oil and acetylene head lamps. This, I am afraid, has been due to the low prices available for the equipments, and this low price has also been responsible for many of the early troubles. Much experience has now been gained and good progress has been made by British makers in solving what is really a very difficult problem owing to the variable engine speed and the uncertainty of output. For example, a motor coach doing long day trips in summer would have an engine speed and period of running time ideal for charging the battery, which might not be required owing to the trips being in daylight. The same chassis put on to winter duty as an omnibus would be continually stopping so that the battery would not get properly charged and it would now be called on to deal with the lighting of a saloon body with about 8 additional lights. Having this continually varying demand in mind it is strange that the popular system of charging to-day is the so-called "constant-current" method in which the dynamo endeavours to supply a constant current irrespective of whether the battery requires it or not. This is inherently wrong, as the current passing to the battery should vary with the state of charge of the battery, a large current for a discharged battery and no current for a fully-charged battery. Now this result can be obtained by the constant-potential method of charging, and the reason it has not been adopted is seemingly the inability of British manufacturers to make a practical constant-potential machine. A further advantage of the constant-potential dynamo is that the lamps can be lit without the battery, whereas in the constant-current system the battery and dynamo are one unit and if disconnected from one another the lamps or the dynamo are likely to be burned out due to excess of voltage. Constant-potential machines of foreign manufacture have been available for many years and have recently been brought to a high state of perfection, and I consider it most unfortunate that the experience of the heavy electrical engineering firms with voltage regulators is not available to meet this competition. Until such machines are available we shall have to put up with the annoyance of undercharging or the expense in battery plates due to overcharging.

For ignition in motor vehicles the magneto still holds the field, the proportion of cars fitted with magnetos being 80 per cent, against 16 per cent fitted with coil ignition. The remainder have dual ignition. Coil ignition made considerable headway until last year, but there is now a tendency to revert to the magneto. Coil ignition gives easy starting and perfectly satisfactory running if the battery is looked after, but we as electrical engineers have no right to expect the motor user to take regular readings of specific gravity to ascertain the state of charge of his battery. It is the duty of engineers making lighting sets either to provide a constant-potential dynamo which will keep the battery charged automatically, or else to invent some kind of dash-board indicator which will show the state of charge of the battery.

Aerial Transport.

Passing from the petrol road vehicle to the aeroplane, there is little in the electrical equipment of the latter which differs from motor-car practice. There is, however, one matter in connection with the production of air-cooled aeroplane engines which is of special interest to electrical engineers, and that is the testing of them. Air-cooled engines are usually tested for endurance and brake horse-power by coupling them to a water brake and running them in an air current comparable with the flying conditions, an electric motor being coupled to the shaft for starting up and running in. The fan supplying the air-blast requires about one-half the horse-power output of the engine, so that in a 100 h.p. engine test-stand 50 h.p. is continuously used in providing the blast and 100 h.p. is continuously wasted in the water brake. With the smaller sizes of aeroplane engines there was little to be said against this, but with aeroplane engines now developing 1 000 h.p. the problem is different. The directors of the Bristol Aeroplane Co. considered the problem carefully and decided that the correct course to adopt was to make the test engine provide the power for the blast, and the only method of doing this satisfactorily was to use an electrical dynamometer. The electrical dynamometer adopted is a 500-volt d.c. generator with the fields mounted on trunnion bearings. The field is kept from revolving by being attached to a spring balance which measure

the torque of the engine, and the speed of the engine is measured electrically by a small generator mounted on the end of the shaft, the revolutions being recorded on an instrument of the illuminated-dial type. The engine to be tested is directly coupled to the dynamometer, which is also used for starting up the engine and running it in. The fan for the blast is mounted at the end of the wind tunnel, and a storage battery and booster form part of the equipment. The method of operation is as follows. Current is drawn from the battery to motor the dynamometer and revolve the engine, and current is also drawn from the battery to run the fan for the blast. When the engine fires, the dynamometer generates and charges the battery and drives its own fan, the torque on the dynamometer being adjusted by varying the current passing into the battery. This current is controlled by a regulator on the battery booster field. The battery installed at Filton has 240 cells and a capacity of 1 950 ampere-hours at the 10-hour rate. With this system a plentiful supply of power is available when required for operating the fans, and the output of the engines is not dissipated in heating water but is usefully converted into electrical energy.

General Remarks.

I commenced my remarks by saying that I would deal with the lighter forms of transport and I have just referred to aeroplane engines of 1 000 h.p. Twenty-five years ago we travelled a long way to see an engine of 1 000 h.p. in a power station, and we were duly impressed by its massive construction and substantial foundations. To-day an engine of this horse-power can be mounted on a framework and can rise from the earth.

Those who are not yet very old have seen the coming of electricity to our towns and countrysides and its use for lighting, heating and power. They have seen the coming of the self-propelled road vehicle, the submarine vessel and the aeroplane, in all of which electricity has played a small but essential part. They have seen the development of the telephone to be an essential part of our business lives; the coming of the gramophone, the moving picture and, latterly, wireless. Most probably they have seen a greater change come over the life of the community than has occurred in the whole period since civilized man inhabited the earth.

We are justly proud of the part which electricity has played in this march of progress and we need not be unduly alarmed at the statistics which show that the units used per head of the population in the large cities of this country are only about 200, against 700 in American cities. There is no comparison between the conditions. We have been reared on cheap coal and we are building up our electricity supply industry on strong and substantial British lines under the guidance of the Electricity Commission. Power stations and distribution systems are under continual improvement and extension and only the best practice is being retained. There is only one flaw in the whole structure and that is the non-standardization of frequencies. General experience calls for a frequency of 50, but it is difficult to see how the large systems operating at 25, 33½, and 40 periods can possibly be changed over. The expense would now be so great that I am afraid it could not be justified.

At the moment the electricity supply industry is embarrassed with a plurality of political patrons, patrons as defined by Dr. Johnson in his famous letter to Lord Chesterfield. In that letter Johnson wrote: "Is not a patron, my lord, one who looks with unconcern on a man struggling for life in the water and when he has reached ground encumbers him with help." The electricity supply industry has been struggling for 35 years, it has now reached firm ground and the patrons have arrived.

Electricity, the strong, reliable and indispensable servant of the public, when viewed through political glasses becomes a beautiful fairy endowed with powers to cure unemployment, solve the housing problem and convert the whole nation into a community of restful button-pressers. I do not presume to express any opinion on the desirability or otherwise of the nationalization of electricity supply, but whether the industry is nationalized or not it is a source of great satisfaction to us all to know that nothing can stop its progress, and we foresee a period of continued activity.

In concluding my remarks I should like to remind you that the primary duty of our Institution is to supply its members with the latest information on the various branches of the industry, and that the volumes of the *Journal* form the most valuable collection of information on electrical matters.

I wish also to express to you my thanks for the honour you have conferred on me in appointing me your Chairman for the current session, and I can assure you that I shall use my best endeavours to maintain the traditions of the office and secure a continuance of the respect which the Western Centre has earned for itself in the electrical world.

IRISH CENTRE: CHAIRMAN'S ADDRESS

By C. P. COOTE-CUMMINS, Member.

(ABSTRACT *of Address delivered at* DUBLIN, *9th October,* 1924.)

When the Members of the Irish Centre elected me Chairman for the present Session a wish was expressed that, in my opening address, I should deal with the question of the training of engineers, this matter being of very great importance to our Centre at the present time when Ireland has, so to speak, attained her majority and commenced to manage her own affairs.

In a general sense engineering consists of the intelligent application of scientific facts and principles to the practical requirements of manufacture and industry, and it follows from this that an engineer must possess a thorough knowledge of the underlying scientific principles of the branch of engineering in which he specializes, and must have also a sound general knowledge of other branches of his profession. To be successful he must of course possess other qualifications, such as initiative, vision, knowledge of men, etc., but without the first two he cannot apply scientific principles intelligently, and a man who cannot do so should not be permitted to call himself an engineer, nor should he be allowed to pose as one.

It is an unfortunate fact that, outside the professional Institutions, there is no clear understanding as to what really constitutes engineering or what qualifications really justify the title of engineer, and it is rather remarkable that this should be so in view of the highly specialized engineering courses which have become a necessary part of all modern universities and colleges, and in view also of the large number of highly qualified professional men who are to be found in the different engineering Institutions; but so it is, and I think that few of you will deny that the ignorance of the general public in this respect is very great.

You may perhaps consider that much of the above is not pertinent to the subject of training, except in so far as it may serve as an argument for a fuller and a better training, but I think that it affects fundamentally the whole question of training. The best training that could be devised for doctors and lawyers would be almost completely neutralized if utterly unqualified persons were permitted to practise, and under such conditions both of these professions would fall back to somewhat the same status that the medical profession enjoyed when the local barber was the recognized medical authority in his district.

My contention is that without the protection afforded by "limited practitioners" the medical and legal professions could not get satisfactory results from any system of training, and that the community would suffer owing to the loss of really able men in these professions. This protection is still denied to the engineering profession and I am convinced that the consequent loss to the community is much greater than is generally realized, and that this loss is only tolerated because the community, having never emerged from the barber-doctor period in engineering matters, is not able to appreciate or measure its loss.

The status that the profession of engineering undoubtedly enjoys to-day, in spite of the lack of protection, is a remarkable tribute to the necessity for qualified engineers and is clear evidence that such a body of men is needed in every country for the purposes of national and industrial development; and unless a country realizes this and takes steps to secure the existence of trained men by according them, when trained, the full professional recognition accorded to the other professions, her industrial development must suffer. This is, I believe, true in every country, but is more accentuated in a country which is in the early stages of industrial development than in one in which that development has already reached an advanced stage. Full professional recognition of the engineering profession is, in my opinion, as much needed for the protection of the nation's industries as it is needed by the medical profession for the protection of the nation's health; for, just as the medical profession can, by virtue of its recognized status, influence and direct public opinion in the right direction, so also should the engineering profession be able to influence and direct it as regards engineering matters. It will, however, never be able to do this effectively so long as utterly unqualified men are permitted to pose as engineers. In the interests of the nation I assert that charlatanism in engineering matters, in these days of rapid engineering development, is as dangerous to true industrial development as it would be to the health of the nation if permitted in the medical profession. It is like a parasitic growth which not only hinders the growth of a plant but makes it almost impossible to propagate healthy plants for future needs.

Of course no system of training can be devised unless there is some agreement as to what an engineer should be, but it seems to me to be equally necessary to arrive at some clear understanding as to what an engineer should do, and I feel that the ignorance of the public in this respect exists largely because professional engineers themselves have not made serious efforts to enlighten it, and I think that before they can do so effectively there must be some real agreement within the profession itself.

Trained engineers with high professional qualifications find an outlet for their energies in many directions, viz. manufacturing, designing, contracting, advising, etc., as well as in the service of the Government, municipalities, local authorities and large corporations, and this very wide field of its activities is, in some respects,

detrimental to the interests of the profession because it brings its members into direct intimate association with the commercial world (the world of buying and selling) to a far greater extent than other professions, and consequently some engineers become, to all intents and purposes, traders, whose main interest and occupation is the sale of certain engineering products or the advancement of certain business interests.

This is, of course, a very contentious subject and I should have preferred to ignore it if possible, but having contended for full professional recognition for engineers because I believe this to be a national necessity, I feel compelled to point out that such recognition involves obligations upon the engineering profession, not the least of which is the obligation upon each member to do nothing which might lower the dignity of the profession in the eyes of the public or of his professional brethren, and although a member is, of course, fully entitled to occupy himself in trade or business if he so desires—and the more qualified engineers in trade or business the better—he should be very careful to keep this always in mind.

I have said that I think the engineering profession should be in a position to lead public opinion, and I suggest that this position would be arrived at more quickly if all members who are directly connected with trade or business were to abstain rigidly from acting as advisers to the general public. Such advice, even though it may be quite disinterested and thoroughly sound, is always open to unpleasant criticism and is largely the cause of the opposition which sometimes exists to the admission of what is called the "trading element" to professional Institutions. I believe that it is a cause of division in the engineering profession and that it hinders that unity which is so much needed.

The experience and knowledge of qualified engineers engaged in industrial and commercial pursuits is far too valuable to be wasted, and I do not suggest that it should be wasted. The assistance and advice of such men should be sought and acted upon, but some machinery should be devised by means of which it could be tendered in a general way through the professional Institutions rather than given directly to prospective clients.

It is not easy to arrive at a satisfactory definition of an engineer in modern times, owing to the diverse occupations to which engineers can usefully devote themselves, but if we agree, as I think we must, that both study and practice are essential qualifications for an engineer, we must exclude from professional recognition all who do not possess, in some degree at least, both of these qualifications. A superior knowledge of either is not sufficient without the other. That is, I think, as far as we can go; it is certainly as far as I feel inclined to go, and crude as the definition may appear I cannot see how we can narrow it down without getting into serious difficulties. The tendency of some professional Institutions to exclude men because of the work in which they happen to be engaged is, I think, a mistake. All that should be demanded in this respect is a rigid observance of professional etiquette, which should as far as possible be the same for all branches of the profession and which should aim at preserving the best traditions of the profession. These, as I understand them, consist of the efforts of the great men of the past to exploit the resources of nature for the benefit of humanity.

It will not, I take it, be disputed that early training during the really receptive years of youth is one of the greatest factors, if not the greatest factor, in the shaping of the after life of the individual. I think that such qualities as resourcefulness, thoroughness in small matters, clear thinking, etc., which are, or should be, part of the equipment of all engineers, are very largely a matter of this early training.

I had the good fortune to be trained in a school, the Royal Navy, in which these very qualities are undoubtedly developed to a very marked extent, and this is, I am sure, brought about by the system known as "Catch them early and break them in young." I passed into the "Britannia" at the age of 12½ years and immediately commenced a specialized training. The training was perhaps too severe to suit modern ideas but it produced men of action and resourcefulness who, within the limits of their profession, knew their business from start to finish, who could be depended on in an emergency, and who had learned to pull together and play the game. Now that result was obtained by means of the right kind of training during the receptive years of early youth, and as far as my experience goes it is not always obtained by means of the ordinary systems of education. Qualities of this kind are essential in engineering work, just as they are in the Naval Service; they were obtained in the Navy by placing the specialized training in the hands of Naval officers who knew exactly what they wanted and made the general subjects subservient thereto. I would suggest that similar results can be obtained by the engineering profession in a similar way.

Of the total number of men who lay claim to the title of engineer a comparatively small percentage have received a university or technical college training, and this must necessarily be so, because only a few can afford to devote themselves to unremunerative work for such a lengthy period as is required to secure a university degree as well as the necessary practical experience, and we must therefore recognize that the majority of those who in my opinion must be classified as engineers obtain the necessary theoretical qualifications whilst they are wage-earners, the most usual course being to attend evening technical classes during apprenticeship. These evening classes are usually conducted in the local technical institute, where the pupil attends for two or three evenings per week, for a course of four or more years. Many excellent engineers have to my knowledge been trained in this way, but the effort required is very great. It is no small thing to work hard all day and then in the evening to make a severe mental effort for two or three hours, when the body is fatigued and the brain, in consequence, is not working at its best. In my opinion, the system puts too great a strain upon all except those whose physique is exceptional, and it is questionable whether even they are not overtaxing themselves. Apart from this, however, the best work cannot be obtained from a tired body, and the results must therefore be most

inefficient when compared with those which could be obtained by the same worker making the same mental effort with an untired body, and in this respect the student at day classes has a very great advantage over the night student. Since night classes provide the only opportunity that the majority have of acquiring the necessary theoretical knowledge, it is obvious that our present system is, and must be, extremely inefficient, and as it makes demands upon the worker which may seriously interfere with his physical fitness it may for this reason alone cause him to be less efficient when trained.

I do not see how evening technical classes can ever be completely dispensed with because, so far as I am aware, they constitute the only method by means of which the adult worker can supplement his knowledge and strengthen his weak points. They are very valuable for this, which is, I think, their true function, but they are not suitable for those who are starting a specialized career, such as engineering, with no other knowledge than that acquired in an elementary school, even though the elementary training may have been ideal, because such a student has, after a full day's work, to cram into about 180 hours per annum an amount of work which the day technical school, or university, student spreads over 1 200 hours.

In our present educational system, evening classes constitute the only method of scientifically training the large majority of our future engineers, but they are not suitable for the purpose, they are inefficient, and they make heavy demands upon the youth of the country. Is it a matter for wonder that so many engineers can be found to-day whose elementary knowledge of scientific principles is far from sound? As I have said, these classes are generally conducted in the local technical institute, which is under the control of the local authority, who contribute to its support out of the local rates, the funds being supplemented from Government sources. This municipal control leads to serious anomalies. The managing committee is generally representative of every interest and section except engineering, and although there is a provision for co-opting members representative of special interests there is no provision for ensuring that the co-opted members have any special qualifications. If engineering representatives were co-opted they would almost certainly consist of engineering employers, who are, as often as not, not engineers at all. It is quite common to find that business men whose knowledge is purely commercial, but who are connected with a business in which engineering processes are carried on, are the recognized authorities upon engineering in the minds of local education committees. Surely there is something wrong with a system which permits of the selection of an engineering teacher by men who have never even heard the difference between a corporate and non-corporate member of a professional Institution, to whom a university degree in Arts is just as high a qualification for teaching engineering as a Science or Engineering degree, and who would, with the best intentions, if left to themselves elect the local wireman to teach a class in dynamo design. I say without hesitation that the administration and control of engineering classes by local authorities is a fiasco, and when we give the matter serious consideration and find that these classes form the only channel for providing theoretical training for the majority of our future engineers, we see that it is more than a fiasco: it is a crime.

The efficiency of the teaching is of course essential in any training scheme, and every effort must be made to ensure that the teachers possess the necessary qualifications and also that they have every facility and opportunity for securing the best possible results. Only those who have experience of it can realize the strain that teaching puts upon an enthusiastic teacher—and a teacher who does not possess enthusiasm should occupy himself in other directions. The proper preparation of the lesson involves a very large amount of time and thought, and the arrangement of practical work in the laboratory, or of lecture-table experiments to illustrate the subject of the lecture, can easily occupy the whole day. After the preparation work is done, and during the two hours, or more, of the class meeting, the teacher must give of his best without pause or sensible slackening, for this is the only way to hold the attention of the class.

Now I think that you will admit that work of this nature cannot be done efficiently unless the teacher gives his whole time to it. If his main work lies elsewhere and requires most of his time and energy, and he arrives at the school only a few minutes before the students, he cannot teach engineering subjects with any real success, because it is impossible for him to give his subjects adequate preparation or to devote any time to the arrangement of experimental work; yet this is the state of affairs generally found in connection with evening classes.

If the main function of the school in an engineering training is to provide the theoretical instruction necessary, with the greatest efficiency and economy, the method of teaching requires very careful consideration, but until engineers themselves are prepared to take an active part and interest in the training system and to collaborate with and assist the teachers, who are at present left to shoulder the whole burden, it is scarcely fair to criticize present teaching methods adversely.

The best method of testing the knowledge possessed by an individual is extremely difficult to decide, and so far no really satisfactory method has been devised. Written examinations cannot bring out the full extent of a candidate's knowledge and they have the great disadvantage that they operate most adversely against those who have a nervous temperament or whose power of expressing their ideas on paper is limited, whilst they give an undue advantage to those who happen to possess a good memory. Although written examinations will probably always be necessary, I think that an oral test should also be made use of under conditions which do not tend to make the candidate nervous, and at least as much weight should be given to the oral test as to the written. In addition, the actual work done by the candidate during the course, provided it has been satisfactory and of the right type, should be considered carefully and given even more weight then either of the above. Whatever the method adopted, it is, I think, most important that

it should be conducted by the professional Institutions and should be of such a nature as to make it possible for any candidate possessing the requisite knowledge to be registered as a qualified engineer, regardless of the channels through which he acquired his knowledge. The standard required should be high as regards both theoretical and practical knowledge, but any attempt to specify the particular channel through which a man must pass in order to obtain full professional recognition would be inadvisable, as it might result in the exclusion of men who in all other respects were most desirable.

The forgoing remarks may be summarized somewhat as follows :—

(1) An engineer must be a specialist with extensive theoretical and practical knowledge.

(2) Men without the necessary knowledge must not be recognized as engineers, and must not be permitted to pose as such.

(3) The existence and provision of qualified engineers is a national necessity.

(4) Full professional recognition and status is essential in order to give effect to items (1), (2) and (3).

(5) Agreement and unity between the different branches of the engineering profession is required in order to secure item (4).

(6) The engineering profession must take an active part in arranging for the education and technical training of its members.

(7) In a scheme for training engineers, evening classes under the supervision of the engineering profession are permissible for adults but are not advisable for beginners.

(8) The training of engineers should not be placed under the control of local authorities.

(9) The technical subjects of engineering should be taught by engineers who should give their whole time to the work and receive adequate renumeration.

(10) A satisfactory test as to qualifications should be devised by the engineering institutions, the passing of which should be accepted as sufficient qualification for admission to membership of the engineering profession.

The best method of giving effect to the above desiderata is of course a matter which would have to be discussed at very considerable length, and time will not permit of my doing this ; in any case such a consideration is more a matter for the joint deliberations of the engineering institutions than for the individual. I think, however, that items (4) and (5) are absolutely vital. Item (5) is entirely a matter for the engineering profession itself, and, if full agreement were reached, everything would depend upon item (4). Without full professional recognition it would be impossible to give full effect to the remainder of the programme, because the conditions of items (1), (2) and (3) could not be attained, and, in consequence, there would not be sufficient inducement to attract the right men to the engineering profession ; with it, the rest of the programme would only be a question of time.

This demand for full professional recognition can only be met by suitable legislation, and if the engineering profession were sufficiently united and insistent the legislators would have to yield to its just demands.

My proposals are so far-reaching that I fear that any suggestions I could make for carrying them out would appear to you to be visionary were I to put them forward as such. I have said that an engineer should possess vision and I have often wished that our really able engineers would occasionally visualize their dreams of the future for our edification; they would, I am sure, prove of exceptional interest. I venture to put before you a vision of the condition of Irish engineering at some future period ; an Ireland in which the word " engineering " embraces all branches of the profession and signifies to the public a national service conducted for the true advancement and industrial development of the country on lines which prevent the exploitation of the country or its resources for the benefit of syndicates or capitalists, and which ensure that a sound and consistent national policy is followed, regardless of sinister influences or vested interests ; an engineering profession limited to qualified men and cleansed from all personal rancours and petty jealousies, in which all members are recognized as of equal standing but in which each member is classified according to the particular branch of the profession to which he properly belongs ; a profession ruled by a central council (containing representatives nominated by each of the branches) controlling such matters as education, professional etiquette, rules of conduct, legislation and the directing of public opinion, and endowed with full powers to prevent engineering charlatanism ; a profession in which each branch is distinct in itself and retains its complete independence as regards its own special technical work, but with a very large number of branches, including civil, electrical, mechanical, municipal, educational, heating, and ventilating engineering, etc., with a trading and commercial branch for those engineers devoting their energies to that class of work ; a profession with room within itself for all men doing engineering work, and only asking for adequate qualifications and a high standard of professional conduct, and embracing all those manifold activities which make up the world of engineering proper, and therefore a profession possessing an influence and control sufficient to direct legislation, and consequently a profession able to hold out the prospect of reasonable remuneration to its members, a profession controlling the education of its members ; by requiring for its recruits a definite type of elementary education between the ages of 12 and 14, a specialized type of education between the ages of 14 and 16, and specialized technical instruction (in day classes from 16 to 20, and evening classes from 20 onwards) for the worker students, with all the specialized instruction given by whole-time teaching members of the profession whose work is supervised by the central council ; a profession which, with the assistance and co-operation of those of its members employing engineering assistants, provides carefully arranged and progressive courses in practical work for those assistants attending day classes, and which co-operates with the universities and technical colleges and provides suitable practical training concurrently with the university curriculum ; and lastly, a profession which undertakes the testing of the final qualifications of all applicants for entry and, in doing so, gives full weight to all the work done by the candidate

during his course, whether theoretical or practical, and, having satisfied itself of his fitness, accepts him as a member, whatever his social position.

Such is the dream I present to you; criticize it as you will, but remember that it is only a dream.

You may perhaps consider that in dealing with the subject of the training of engineers I should have gone into more details as to the actual training methods and teaching syllabuses. These are, of course, branches of the subject upon which much might be written and I have very definite views regarding them, but I have purposely not expressed these views because I feel that they are details which must be settled by the engineering profession acting as a whole when it has obtained full professional recognition, just as the training for the medical and legal professions has been arranged and elaborated by those professions.

The whole question of the education of engineers is of such vital importance to the engineering profession that it may finally prove to be the common platform upon which the different branches of the engineering profession will eventually come together.

NORTH-WESTERN CENTRE: CHAIRMAN'S ADDRESS

By H. C. LAMB, Member.

(ABSTRACT *of Address delivered at* MANCHESTER, *4th November*, 1924.)

We meet again at a time when there are several good reasons, I think, to be hopeful about the near future of the electrical industry, one reason being that public opinion has become more convinced than ever before that one of the chief needs of to-day is a greater application of electrical power to the business of life in all its branches. Electrical engineers, of course, have been preaching this doctrine for many years, but the encouraging thing is that writers in the popular Press are now emphasizing this point, and the necessity for a national policy with regard to the development of the electric supply industry is generally realized.

In the public discussion of the subject by laymen, it is too often disappointing to find that those taking part fail altogether to do justice to the good work of British engineers, and that little seems to be known of the sound, though unsensational, progress which has been made. It is, of course, all to the good that the principles underlying the charges for electrical energy should be understood by the general public, and that the great importance of load factor and diversity factor should be appreciated, but, unfortunately, there is a tendency for some of those who take part in the popular discussions on the subject to divide themselves into two camps, one of which says that the comparatively limited development of electrical power in this country is evidence of the failure of private enterprise, while the other is equally positive that the situation indicates the limitations of public ownership. This is an intensely interesting aspect of the subject, but a very thorny one, and it is perhaps unnecessary for me to say that I propose to leave it severely alone to-night.

At the present rate of growth, the output of the public supply stations in the chief towns will double itself in 4 or 5 years—a rate of advance which, in any other industry, would give cause for immense satisfaction, but as ours is expected to grow at a phenomenal pace, something better is demanded.

CHARGES FOR ELECTRICITY.

It is often said that, owing to supply charges being too high, development is slower in this country than it might be. It is hardly necessary for me to call attention to the very great part which water power plays in those countries which are most advanced electrically, and, as the fuel cost is 75 per cent of the total operating cost of a modern power station, it is clear that generation by water power must have a considerable influence on selling price.

On this question of price it is only natural that frequent reference is made to America. It is no easy task to make comparisons between British and American supply tariffs, because no two are alike, but a close scrutiny of the charges in force in the principal towns leads to the definite conclusion that, while the flat rates for lighting are, on the whole, lower in America than here, the rates for power are practically on the same level.

As regards the industrial power supply section, it is, I believe, a fact that the most advanced British municipalities and power companies have secured as great a proportion of the potential demand as have similar undertakings anywhere else, although, of course, there are still vast possibilities in this direction.

DOMESTIC SERVICE LOAD.

It is in the development of the domestic service load that we are behindhand, in spite of the fact that there does not appear to be anything in America so favourable to the consumer as are the two-part tariffs in common use here, with a fixed charge based on the rateable value of the house, plus a low rate for energy consumed; and yet the number of domestic consumers in British towns is only a small fraction of what it should be. In the Manchester area, for instance, electricity is used in 10 000 dwelling houses, which is only 5 per cent of the whole number, and is typical of our own towns.

generally. In the most progressive towns in America a supply is given to 80 per cent, or even more, of the houses, and it must be admitted, I think, that this difference is chiefly due to the much greater enterprise shown there.

One would like to take this opportunity of acknowledging the very generous response which is invariably given by power supply undertakings in the United States for information regarding the methods which have assisted in their rapid progress. Briefly, the problem was the same in the American towns a few years ago as it is here to-day, namely, what can be done with the unwired house. It was solved by the adoption of a deferred payment system for wiring and fittings, financed in some cases by the supply companies themselves, in others by the banks working in conjunction with associations of wiring contractors. The tariffs in force in almost all English towns to-day are sufficiently attractive to ensure that practically all *new* houses of any class are wired for the use of electricity, but it seems impossible to secure the old houses in any great numbers without some scheme of free or assisted wiring.

In the same way, it is the first cost of electric apparatus which prevents its use by the general public. For example, up to a year ago only 100 electric cookers were purchased and installed by consumers on the Manchester mains, whereas in the first year of a public hiring scheme 500 were connected. One great advantage of public hiring and maintenance schemes is that the experience gained rapidly leads to improvements in design. The records of failures show the general weaknesses and make it possible to specify features essential to success. If rapid progress is to be made, it would appear that more apparatus must find its way from the manufacturer to the consumer through the supply authorities. This method inspires confidence, because the consumer knows that untried and untested articles will not be recommended to him, and that, in case of accidents, satisfactory repairs will be carried out at a reasonable cost.

Street Lighting.

Another direction in which the consumption of electricity may well show a considerable increase is in the public lighting of the streets, for in recent years there has been a marked raising of the standard of desirable illumination. This is, no doubt, partly the result of the improved lighting in shops and public buildings, due to the general adoption of lamps of the gas-filled type, and the more effective glassware now available, but it is in a much greater degree the result of the conditions arising from the very pronounced growth of high-speed traffic. It is well recognized, both by motorists and by police authorities, that adequate road-illumination is most effective in reducing the risks inseparable from such traffic.

The most striking difference between old and modern methods of street lighting arises from the fact that the lamps are now regarded as sources of illumination, whereas formerly they were merely beacons placed at intervals for the purpose of indicating, more or less effectively, the line of a roadway, just as buoy lights are used in the channel of an estuary. The following may be regarded as desirable values of the minimum illumination on the horizontal plane at ground-level midway between lamps :—

For important street-crossings and public squares, etc., in cities where traffic is dense
0·5 to 1 foot-candle, or more.
For important main thoroughfares
0·3 to 0·5 foot-candle, or more.
For secondary thoroughfares .. .. 0·1 foot-candle.
For side streets and streets in residential districts
0·05 foot-candle.

Some of these values may appear to be on the high side, but there is little doubt that they will eventually be exceeded.

Despite the relatively high efficiency of flame arc lamps, they are being rapidly superseded by gas-filled incandescent lamps, mainly owing to the lower capital charges and maintenance charges of the latter, but also because they are much more reliable and are more suitable for use with the modern scientifically-designed directive glassware.

As an "all-night" street-lighting load has a load factor of well over 40 per cent, it is obviously a very desirable one, and more particularly so in the case of residential districts. The only disadvantage is that it is essentially a peak load, but there is every indication that the importance of this distinction is rapidly disappearing. Depending upon the standard of illumination adopted, the load will vary from 5 to 25 watts per yard of street.

The announcement that the electrification of the Manchester to Oldham railway line is to be proceeded with, is one which will be welcomed by all electrical engineers, and will, at the same time, bring renewed hope to many thousands of long-suffering suburban travellers, some of whom spend a weary 20 minutes every morning in a railway train, in order to cover a distance of 4 miles.

Nothing would give greater public satisfaction than a sign that a forward policy was to be adopted by the railway companies in respect of railway electrification.

The Super-power Station.

It may be said, without fear of contradiction, that the super-power stations erected in the last few years have fully realized the high expectations of those responsible for them. They contain some of the finest products of British engineering, and are operated in a manner unsurpassed anywhere as regards the care which is taken to secure the highest working efficiency. One sign of the interest they have aroused is in the constant stream of engineering visitors which they attract from all over the world. The high thermal efficiencies predicted, the economy of labour, and low working costs have all been realized.

High Steam Pressures.

The stations now operating at 375 lb. steam pressure have a coal consumption per kilowatt-hour which is about one-half of what was usual 20 years ago; when the steam turbine came into general use. A further gain of 8 per cent can be made by raising the initial pressure to 550 lb. per square inch and reheating the steam once, whereas if, instead of stopping there, the

pressure were raised to 1 200 lb. per square inch, and the steam reheated twice, it is estimated that 20 per cent would be saved, making it possible to obtain station overall thermal efficiencies of 26 per cent when using very large units. Plant of this kind, of course, means high capital cost, and no doubt its justification will depend on the future price of fuel.

It looks as though the ultimate possibilities of high-pressure steam will be explored before very long. Boilers have been ordered for a working pressure of 1 200 lb. per square inch—not, as might be supposed, small experimental units, but, on the contrary, designed on the scale common in big power stations to-day, having steam and water drums of forged steel with walls 4 inches thick.

Benson Boiler.

One of the boldest experiments with high-pressure steam is the Benson boiler, which will have nothing to do with half measures, but goes at one jump to what is called the critical pressure of 3 200 lb. per square inch. It is an arresting fact that, at this pressure, the steam has no latent heat, and its volume is no greater than that of an equal weight of water at the saturation temperature of the steam.

The experimental plant which has been constructed at Rugby consists of small-bore steel tubes, in the form of a number of vertical spirals. Distilled water is continuously fed into the bottom of the spirals at a constant pressure of 3 200 lb. per square inch, and, as it rises in the tubes, its temperature is gradually raised to 706° F., when it passes into steam without any boiling process (in the ordinary sense of the words). I understand that the turbo-plant to operate in conjunction with this boiler has been completed, and the results of the tests which are now in progress will be awaited with much interest.

The raising of steam pressures has brought certain troubles with it, but these are almost entirely confined to the accessories of the main plant, and will soon be overcome. One of the chief difficulties has been the rather serious waste of steam which occurs through the scoring of the faces of safety valves and drain valves, when they are called upon for throttling action at very high temperature and pressure. Unequal expansion and unsuitable materials have been the chief causes of these troubles, but many improvements have recently been made.

Boiler Priming.

The fear was often expressed that high-pressure, high-duty boilers would give serious trouble through priming. Experience with a large battery of boilers worked at 375 lb. per square inch, and having steam and water drums exceptionally small in proportion to the evaporative capacity, goes to show that very little priming takes place so long as proper care is given to the condition of the feed water.

Boiler Feed-water.

The rate of evaporation for a given heating surface is now double what it used to be, and the high-duty boiler of to-day requires water of exceptional purity both as regards soluble matter and dissolved oxygen. Unless the water supply is very good, it is necessary to install evaporators for the make-up water which, in any case, should be kept down to the minimum quantity possible. Every precaution has to be taken to prevent loss of water, and the slightest leakages should be stopped. If once pitting of boiler tubes is allowed to start, it becomes very difficult to arrest, and it is now recognized that the main cause of corrosion in boilers, economizers, and sometimes in turbine blading, is dissolved oxygen in the feed-water. The closed feed-water systems of to-day, designed with the object of rigidly excluding air, are a great contrast to the old method of open tanks with water spraying from a ball valve and assisting to the maximum degree the process of dissolving oxygen from the atmosphere. The new method can be entirely successful, but only if great care is exercised.

In spite of what has sometimes been said to the contrary, a tight surface condenser, working under high vacuum, is an efficient de-aerator, provided that the make-up water is injected in a fine stream. Under these conditions, the amount of dissolved oxygen present when the condensate leaves the condenser can be as low as 0·07 cubic centimetre per litre, and this small proportion is probably harmless.

Condenser-tube Corrosion.

Another problem receiving a great deal of attention in power station laboratories is condenser-tube corrosion. The fear of dirty and corrosive circulating water getting into the boiler feed through a broken condenser tube is somewhat of a nightmare. One of the difficulties is that the problem is usually entirely different at each station, and it is necessary to carry on independent investigation. Most valuable work has been done at many places, and it might help towards a solution of this complicated problem if all the information obtained, where condenser-tube corrosion is experienced, could be collected and published by one of the Institutions.

Experience shows that the forecasted working boiler-efficiency of 85 per cent can be maintained over an indefinite period, but this is only possible when some process is adopted for keeping the heating surfaces continuously clean. In the early days of the steam-jet blowers, much damage was done by improperly directed jets and many tubes were ruined, but this trouble has now been overcome, as well as the difficulty of obtaining material which will live in the first pass of the boiler.

Grit Arresters.

A recent improvement which should always be installed in combination with soot blowers, when solid fuel is used, is the cinder catcher. From the æsthetic point of view, the modern system of fan draft and short steel chimneys is much to be preferred to the old skyscrapers, but there is no doubt that in many cases a nuisance has been caused by the great quantities of grit discharged from such chimneys. The first attempts to overcome this trouble were not altogether successful, but catchers can now be obtained which will eliminate 90 per cent of the solid stuff from the chimney gases, and many tons of gritty dust which would otherwise be deposited in the near neighbourhood of the station are collected and transported to the ash tips.

Air Preheaters.

Another new feature of the boiler house, of which there is comparatively little experience, is the air preheater. Only a few years ago, there was much scepticism regarding the use of air heaters. The first point in doubt was whether the tubes, or other classes of metal channel employed, could withstand the corrosive action of the flue gases for a reasonable length of time, and secondly, whether the calculated economy would be borne out in practice.

With regard to the first of these points, it is well known that the flue gas contains acid sulphates, which readily attack mild steel in the presence of moisture. The important point in the operation of air heaters is, therefore, that the gases should never be cooled to so low a temperature that deposition of moisture takes place. It is, perhaps, too early yet to speak confidently, but the evidence so far goes to show that a life of 10 or 15 years may reasonably be expected for air heaters.

Some trouble, through the burning of grates and the destruction of brickwork, has been experienced when an air temperature of 350° F. has been exceeded. In fact, it is doubtful whether even this temperature will be found to be economical, as it will certainly cause increased furnace maintenance costs, but at moderate temperatures, such as 200° F., air preheating has been an unqualified success, and the expected increase in boiler efficiency has been fully realized. Combustion in the furnace is greatly improved, and the combination of air preheater with the very large furnace volumes of to-day produces an entirely smokeless result. This last point is particularly important, as much in the interest of our own industry as in that of the whole community. The growing pressure of public opinion will some day force smokeless combustion on all industrial concerns, and if the power supply plants lead the way, as they should, the chances of public favour and new business are greatly improved. The public smoke inspector should be an important, though purely honorary, ally of the electricity supply authority.

Super-tension Cables.

An entirely different subject, but one of particularly absorbing interest is the future, or perhaps I should say the present, of the super-tension cable.

The schemes which are developing for distributing power over wide areas from a small number of large plants, depend for their success, in this country at any rate, on underground transmission at high voltage. Interest was undoubtedly stimulated by the announcement of Government intentions to use the powers of the State for the purpose of furthering a scheme of new transmission lines, and one may perhaps be permitted to hope that certain very recent events will not cause any reversal of that policy.

An important question in connection with super-tension transmission is whether single-core or multicore cable should be adopted. In this country multicore cable is chiefly favoured, but on the Continent the tendency has been for a long time, and apparently is still, to use single-core cable. The chief claim made on behalf of single-core cable is one which must appeal strongly to all those who have responsibility for maintaining continuity of supply in large electrical systems. I refer to the claim that, as the insulation of the conductors is subject only to the dielectric stress between phases and earthed neutral, the automatic protective gear will be called upon solely to deal with faults to earth, and not with short-circuits between phases. It has been the custom to think and speak of high-tension cables as never breaking down, except through faults having an external origin. For the higher voltages now coming into use this no longer holds good, and the shock of a short-circuit at a pressure of 33 000 volts or more, even when the fault is several miles from the generating plant, is very severe, especially on a big system with several power stations and a great deal of converting plant feeding into the fault. The claim, therefore, that short-circuits would be eliminated by the use of single-core cable is one which merits the fullest consideration. It should be remembered, however, that two simultaneous earth faults on different phases are quite a possibility, and amount to much the same thing as a short-circuit, and it has been found in practice that, unless great care is exercised, the damage caused by a fault on a single-core system is not confined to the area in which it originated.

Another claim made by the advocates of single-core cable is for increased current-carrying capacity, due to better dissipation of heat and a reduction in the mutual heating between cores; also, that a fourth cable, on a three-phase system, constitutes 100 per cent spare on the assumption that it can be used to take the place of any one of the three cables forming the main.

These claims are of doubtful validity, particularly the last, which would involve switching complications and would prevent the triangular formation of the cables that is so desirable.

With regard to jointing, it is claimed that single-phase joints are less likely to break down than three-phase joints, but this claim is discounted by the fact that there are three times as many of them, which is important in view of the difficulty experienced in maintaining watertightness of the boxes.

One disadvantage of the single-core cable is that, armouring throughout being inadmissible, the cables are more liable to damage during laying than are three-phase armoured cables; and another is that the system is less flexible and not so adaptable to the varied conditions and requirements of an underground transmission line, particularly in cities.

Probably the chief point against the single-core system is the substantially greater cost of manufacture, laying and jointing, as compared with the multicore system.

It may be that consideration of capital charges and eddy-current losses will fix a minimum pressure for the commercial use of single-core cables, and that manufacturing difficulties will fix a maximum for multicore cables, and further, that these two limiting figures will not be very far apart, possibly in the neighbourhood of 50 000 volts.

It is, I believe, a gratifying fact that British makers stand first in the world in the manufacture of super-tension multicore cables, and it is no doubt correct to say that there is more of such cable in use in this country than anywhere else. The 33 000-volt underground line

for connecting the supply systems of Manchester and Salford was not quite the first example of the kind, although it was the first in Great Britain. It has been in continuous use for five years—so far, without a black mark of any sort on its record. Since then, over 60 miles of cable for this pressure have been laid down in Manchester and the immediate neighbourhood, and there are, of course, many other installations—some at even higher voltages—in England and Scotland.

Although there are hundreds of miles of underground cable working at 20 000 and 22 000 volts with entirely satisfactory results, it is no secret that a certain amount of trouble has been experienced, both with joints and with cables, at voltages above 30 000, and that it has been necessary in some instances, alike in this country, on the Continent of Europe and in America, to make temporary reductions in working pressures. This applies both to single-core and multicore systems. It is right to emphasize the fact, however, that practically all manufacturers and users are convinced that such reduction in working voltage is only a temporary measure, pending certain alterations, and in some of these cases the normal pressure has already been restored. Troubles have been due to various causes. In the first place, these main transmission lines have often to be laid very deep in the ground, which increases the difficulty of keeping water out of the joints.

With regard to breakdowns of the cable itself, a striking point is that very slight changes in manufacture appear to make all the difference between failure and success. The absolute exclusion of air, the removal of the last trace of free moisture from the materials, and tightness of the dielectric, are no doubt essential to success. It would appear that changes of temperature, following the rise and fall of the load, cause movement of moisture and of the impregnating oils, which may result in breakdown, even after the cable has stood up to a test far more severe than the normal working pressure.

Owing to the relatively large proportion of dielectric, super-tension cables are somewhat weak mechanically, and require much more careful handling and laying than those for ordinary pressures. It has even been suggested that the cable should be manufactured in straight lengths, and not coiled on to drums; but that, of course, is going to extremes. Electrically, the unbalanced static potentials existent in the usual 3-core formation would appear to present a more difficult problem than the maximum potential gradient on the layers of dielectric immediately adjacent to the conductors.

A great amount of research work has been carried out, and the considerable practical experience recently gained will, it may be said with confidence, soon bring the super-tension cable up to the same high standard of reliability as has been attained by those working at more usual pressures. More than this could not be desired. In the meantime, credit is due both to those manufacturers who have done the pioneering work which has made possible the super-tension cable, now so essential to electrical development, and to those authorities in the electricity supply industry who have not been afraid to shoulder considerable responsibility in its extensive use.

Protective Gear for Large Systems.

The rapid development of large transmission systems has increased the importance of automatic protective apparatus, and the nature of the breakdowns experienced on these systems may have a bearing on the future design of the protective gear.

Practically all failures of cables at pressures up to 11 000 volts have originated as faults to earth, and, for that reason, it has been possible to clear them by means of discriminative protective apparatus before short-circuits between cores have developed. On the other hand, with voltages over 30 000 it has, unfortunately, been the case that breakdowns have been due to short-circuits between two cores, and, in spite of the quick operation of protective gear, it has not always been possible to isolate the faulty feeder with sufficient rapidity to prevent a serious disturbance of the whole system concerned.

The advantages of simplicity and reliability in the design of this protective apparatus are now widely recognized, but there is still room for further improvement, as even the most modern types have not been entirely satisfactory in practice. Much of the trouble has been caused by the weak mechanical construction of the relays, although it is clear that the best possible workmanship is not too good for relays controlling feeders each one of which may have a load of 15 000 or 20 000 kW.

Another point not sufficiently appreciated in the design of protective apparatus has been the extent and effect of the comparatively heavy capacity-currents in 33 000-volt mains, and, consequently, gear of the highest repute has failed to retain its stability under the capacity-current conditions arising from a severe system disturbance. There is, however, every indication that, by rendering the relays partially immune from the effects of currents of abnormal frequency, and, if necessary, reducing the sensitivity of the operating settings, it will be possible to overcome the capacity-current troubles, and the effects of the heavy through-current caused by short-circuits, or excessive overloads, on portions of the system outside the protected zone.

Various systems of generator protective gear have been in successful operation for many years, but the combined protection of generator and step-up transformer, which is now becoming necessary in many cases, has not always been quite so successful, owing to the unbalanced component of the circulating current introduced by the magnetizing current of the transformer.

Outdoor Switchgear.

A good deal of interest attaches to the large 33 000-volt outdoor switching equipment installed in Manchester more than a year ago. So far, the operation of this equipment has been entirely without noteworthy incidents of any kind. There was some natural hesitation, at the time when the installation was designed, as to whether such an experiment could be a success under the peculiar climatic conditions of this city. Now that these fears have proved groundless, it is likely that other similar installations will be used, not so much, perhaps, in cities, as in schemes for rural electrification.

NORTH MIDLAND CENTRE: CHAIRMAN'S ADDRESS

By THOMAS BOYES JOHNSON, Member.

"THE VOCATION OF THE ELECTRICAL ENGINEER."

(ADDRESS *delivered at* LEEDS, 11*th November*, 1924.)

No one can read the reports of the proceedings * at the Commemoration Meetings of this Institution held in February 1922, without being struck by the enormous development of engineering during the last 50 years. Dealing with electrical engineering, it seems incredible that at the time of the birth of many of us electric lighting was practically unknown, the telephone had not been invented, electric trams and railways had not been thought of, whilst wireless telegraphy and telephony—which have now attained such universal prominence—were not even dreamt of. The dynamo entered the area of commercial use less than 50 years ago, and it still seems almost miraculous that the turning of a mass of iron enclosed in wire in an electromagnetic field should give us lighting, heating, traction and power in such various ways and to such an enormous extent as we have to-day.

There is no reason to think that there will be any slackening in the field of discovery or in that of practical application. As Prof. Howe remarked at the meeting of the British Association in August last: † "We can look forward with confidence to an ever-increasing application of electricity to the utilization and distribution of the natural source of energy for the benefit of mankind."

It follows that the world at large must have been profoundly influenced by the engineering achievements of the last half century, and that the engineer must have influenced the conditions and amenities of life to a very great degree. It is certain that he will continue to influence them to an equally great degree in the coming years. Fortunately the work of scientific research is now recognized more generally than was formerly the case, and various administrations and organizations are satisfied that it is worth the cost. On the work of the scientists depend the practical applications which ameliorate the conditions of mankind and the improvement of our industries.

Among the developments lying immediately in front of us is that of the national power resources. To replace the wealth which has been destroyed new wealth must be created, and this can best be done by drawing on the resources of Nature's great treasure house. It is interesting to note that so far back as 1875 Lord Kelvin recommended—as modern investigators and politicians also do—that power stations should be situated near the coal mines, and the power transmitted from there, instead of coal being carried to the places where needed. It is unfortunate that the provision of power on a large scale is largely hampered by what Sir John Snell calls "intense municipal feeling," and, in view of the need of such development and of the great advantages which could be derived from it, it is hoped that the Electricity Commissioners will soon be able to make greater progress than they have hitherto succeeded in doing. The utilization of waste heat and exhaust steam, the most economical methods of using coal, and the use of oil and alcohol—all present opportunities of considerable development in the near future. When the public becomes aware of what a good and cheap supply of electricity for the whole country could do to promote its welfare, it will demand the promised boon and will sweep away obstructions whether these be municipal or the vested interests of companies.

Dr. Landor, the Director of Fuel Research, describes the fuel problems as follows:—"First, the utilization of coal in a manner which will render available the largest possible proportion of the potential heat which it contains; secondly, the obtaining from our coal resources of oil in sufficiently large quantities to render us to some extent independent of imported supplies—this is doubly important since the imported supplies are in the main controlled by our industrial competitors; thirdly, for industrial and domestic purposes the obtaining of an adequate supply of a more smokeless type of fuel, the use of which would effect to the nation considerable economies in other directions."

At the World Power Conference at Wembley, Prof. Gibson expressed a hope that a large extension of water-power plant in the United Kingdom could be obtained economically. The further development of water power for large stations will doubtless depend on the success of the Severn experiment, but it may be pointed out that the Chester Corporation have for some years obtained power for electric tramways from the River Dee, and that small hydro-electric plant is stated to be very economical in comparison with larger installations. In countries such as the United States, Canada, Scandinavia, etc., the developments may be enormous.

THE SMOKE PROBLEM.

Another of the important questions urgently calling for solution is the diminution and eventual abolition of the smoke nuisance. Sufficient figures have been quoted to show the wastefulness of our present methods of consuming coal and that it would be economical to alter them, but what cannot so readily be shown in figures is the enormous damage to life and health caused

* *Journal I.E.E.*, 1922, vol. 60, p. 377.
† *Electrical Review*, 1924, vol. 95, p. 239.

by the conditions under which we live. All our great cities are under an unnecessary pall of smoke which robs us of many hours of sunshine per year and damages not only the health but the temperament of people. It has been shown over and over again that smoky districts invariably have a high infantile death-rate, and it is not a matter of coincidence but of cause and effect that the most discontented people and those most ready to fly to violent remedies are the inhabitants of smoke-laden cities. In 1923 the diseases classed as "rheumatic" (which are notably affected by the absence of sunlight) cost the approved societies 2 million pounds in sickness benefit, and the nation 3 million working days of insured persons alone. In Leeds thousands of pounds a year are spent on the additional washing of men's collars owing to unnecessary smoke and dirt. The smoke nuisance is tolerated largely because we have grown up with it, and also because of the strongly ingrained impression that "dirt means wealth." It is high time that people realized that the wealth can be produced without the accompaniment of so much dirt. If the political parties can be convinced that the question of smoke abatement is one on which votes can be obtained, a speedy improvement will be seen. The time has come for a strong lead to be given by the various Institutions, and the Government should give a time limit to all factories using raw coal. Manufacturers would then take care that, in making any alteration or extension, electrical driving would be provided for in anticipation of the compulsory change.

There is also the question of domestic coal fires. Every effort should be made to spread the use of electrical appliances for domestic use, and as showing the magnitude of the task in this country it may be pointed out that in the United States of America there are more than 11 million homes wired for electrical service. Municipal corporations should become alive to the fact that a policy of taking profits from electricity, gas, water and tramway undertakings, in order to reduce and camouflage rates, is a great mistake. After making provision for interest, repayment of capital, and depreciation, the balance should be devoted to the spread of the use of electrical, gas and tramway undertakings. To the average citizen this would be a positive gain financially, while from the point of view of health and cheerfulness the gain would be much greater still. It is satisfactory to learn that the Glasgow Corporation have decided to install Maclaurin producers for the manufacture of smokeless fuel and the provision of gas at the Dalmarnock generating station. Extensive experiments with such plant have shown that a satisfactory smokeless fuel can be produced and sold at a price equivalent to that of coal when regard is paid to its calorific value, and that the gas produced can be used for firing steam boilers. Many of the large modern buildings in London are heated by steam from boilers fed by oil fuel, and this practice seems to be making considerable progress. At Nottingham a scheme has been adopted for setting up plant at pit-heads which are quite near to the city, where the coal will be treated by a low-temperature carbonization process, producing a supply of gas for the city mains and leaving behind a residue of oil and smokeless fuel. It is claimed that this scheme will make Nottingham the first smokeless city in the country.

Telephony.

It seems almost incredible that the first telephone exchange was established so late as 1878, while to-day there are well over 20 million telephone exchange stations in various countries, nearly $1\frac{1}{4}$ millions being in Great Britain. The first multiple exchange was established 10 years later, and by means of these multiple boards one operator can have access to 10 000 lines. It is physically impossible for one operator to obtain access to a greater number. With the development of the automatic system, however, this limitation disappeared. The first automatic exchange in this country was opened at Epsom in May 1912, and several others were completed in 1915 and 1916. The first large city to be provided with an automatic exchange was our own city of Leeds, where, in spite of serious difficulties owing to the war, a 5-figure exchange constructed by the Automatic Telephone Manufacturing Co. was opened in May 1918. This was the largest automatic exchange in Europe, and the largest in the world to be transferred from the manual to the automatic system. It is still the only 5-figure exchange in Great Britain, but a similar one is being constructed in Sheffield, other automatic exchanges are being provided in various towns, and the conversion of the London system to automatic working has been commenced. A 4-figure exchange at Grimsby constructed by Messrs. Siemens was opened in September 1918, and proved equally satisfactory. Another 4-figure exchange has just been opened at York, and the conversion of the Leeds suburban exchanges to automatic working is proceeding steadily. A 4-figure exchange at Harrogate has been commenced, one at Halifax will be started as soon as the building is ready, and others will follow at Wakefield, Keighley and other places within the area of the North Midland Centre. The Hull Corporation have also opened two automatic suburban exchanges. We are glad to know that the system in Leeds has proved the advantages of automatic telephone working, and that the Post Office authorities are now definitely committed to the establishment of automatic working as the standard method for large exchanges.

Another important development in telephony has been in the distance over which speech can satisfactorily be transmitted. In Graham Bell's first business circular it was stated that telephones could be furnished for the transmission of speech through instruments not more than 20 miles apart. With the improvement of lines and apparatus the distance was largely increased, but was still limited. Continued attempts were made to devise a telephonic relay to repeat telephone currents in the same way as the well-known telegraphic relay, but all these proved unsatisfactory. With the invention of the thermionic valve or repeater, however, the difficulty disappeared, and there is now practically no limit to the distances over which speech can be transmitted. Speech is already carried from East to West of the American continent, and there is no technical

reason why it should not be carried equally well between the extremes of North and South America.

Improvements in the condition of the lines used for telephone working have been remarkable. For many years it was necessary to use aerial wires, owing to the limited distance possible with gutta-percha-covered or rubber-covered conductors. Air-space cables increased the distance considerably, and the invention of the loading coil straightway enabled the distance to be increased about threefold. In 1913 the first balanced cable for both telegraph and telephone wires in this country was laid between Leeds and Hull, and proved so successful that the laying of such cables for long-distance telephony became the standard practice. This balancing enables thermionic repeaters to be used, and telephonic communication by means of balanced cables, loading coils and thermionic repeaters can be carried on from one end of the country to the other.

International Telephony.

It will be remembered that Mr. Gill during his presidency of the Institution devoted great attention to the development of international telephony, and the development of this phase of telephony will undoubtedly occupy a prominent position in future. Here, again, the invention of the thermionic valve opened up a new era. By its means the British military authorities were enabled to have telephonic communication between London and the Expeditionary Force Headquarters in France. The Germans with the great advantage of land frontier had circuits from Berlin to the Army Headquarters in Northern France and Russia, and also right across Austria and the Balkans to Constantinople. Owing to its geographical position, as well as for other reasons, Germany is bound to occupy a large place in any scheme of European intercommunication. At the international conference held in Paris last year, at which Belgium, England, France, Italy, Spain and Switzerland were represented, much work was done in getting unanimous approval to many important technical proposals which were officially confirmed by the Governments of those countries, and further progress was made at a record conference in Paris in April last when no fewer than 21 European countries were represented. It is much to be hoped that Mr. Gill's plan of an international board for constructing, maintaining and operating long-distance circuits will be adopted. The influence of such an association and of international telephony would extend far beyond the boundaries of telephone working, and be of great service in creating and maintaining good feeling between the peoples of different countries, thus removing national misunderstanding, inspiring confidence and removing friction.

The Vocation of the Engineer.

If the electrical engineer has so much influence over the lives of fellow citizens and the conditions under which they live and work, it follows that whether employed by the State, a municipality or a limited company, he is in the best and most complete sense of the term a public servant, and he should realize the obligations which this places upon him. The education and training of the engineer are of great importance and have been dealt with in various addresses to the Institution. The pay of the engineer is also of importance, and the Institution should, without undue interference in wages questions, use its influence to raise the general standard of remuneration of engineering officers and men. In this connection reference is gratefully made to the letter sent by the presidents of the professional and technical institutions to the Prime Minister in February last, in which the greater recognition of scientific and technical men in the Government service was urged. It is wrong, for instance, that engineering workmen of long experience and training, and of great skill, should be receiving less wages than unskilled labourers in some occupations.

Of greater importance is the character of the engineer and the spirit which animates him. Realizing that the public depends upon him to so great an extent, the engineer will look upon his work not merely as an occupation by which he can earn a certain amount of money, but as a vocation. The public is entitled to the best service he can give, and a high ethical conception must be put on his duties.

There is one way, in particular, in which the electrical engineer can be of very great service in an important direction. Writers and speakers generally refer to capital and labour as if these were the only two classes affected in industrial matters, whereas the great bulk of the members of the Institution do not come within either of these categories, but are supervisors, etc. The ownership of factories in the North of England has changed in such a way as to alter largely the character of local life: whereas formerly the great productive concerns were owned and conducted by strong, shrewd men who had climbed out of lower ranks, their descendants have largely sold out to company promoters. Many men who still continue to be directors have mostly gone to reside at a distance, and their interest in the place of their origin, and in the community from whom they have derived their ample means, is ended, except for the limited duties of the board-room. With the decrease of private ownership which goes on at an increasing rate year by year, the old relations between the employer and his workmen are practically dead, with the result that there is a large amount of misunderstanding, distrust and fear between them. The engineer, whatever his supervising grade may be, can do a great deal towards filling the gap. He can represent the requirements of the employers to the men in a reasonable light, instead of simply issuing orders, and can receive suggestions or, if necessary, remonstrances, from the workmen, and represent them to the employers or directors. Many of the most serious industrial troubles of recent years have undoubtedly been due to misunderstanding and suspicion, and the engineer who shows himself worthy of trust by both parties, and loyal both to those above him and those below him, can exercise a very valuable influence in minimizing trouble. Engineers stand between capital and labour, and also between the public and its safety, and by their education, training, and sympathy with all classes seem specially competent to work out a solution of the industrial problem.

The engineer must look upon himself as a trustee and cultivate a high sense of the importance of his duty—which is not a question of self-importance—to his superiors, his subordinates, and the public. Employees must not be treated as machines or "hands" but as brother men engaged in improving the conditions of life and furthering the progress of mankind. There must be a spirit of real comradeship, which will have a high spiritual value and help to inspire the spirit of service in others. As has been well said, "The greatest service a man can do is to carry out his daily work in a spirit of service to God and man."

SCOTTISH CENTRE: CHAIRMAN'S ADDRESS

By ALEXANDER LINDSAY, Member.

(ABSTRACT *of Address delivered at* GLASGOW, 11*th November*, 1924.)

To-night, after some general remarks, I propose to refer more particularly to a matter of topical interest—The Cultivation of, and Distribution for, the Domestic Load. In fact, to give it a slogan, let us have "Electricity for the Million."

Whenever we have a few quiet moments it is interesting to look back and record progress. In 1924, it is not only interesting but instructive to look back and note the growth of Electrical Science, Electrical Industry and Electrical Institutions.

Taking the last-mentioned subject first, it is 53 years ago since the Society of Telegraph Engineers was formed with 66 members. In 1900, when my association with the Institution began, the total membership was 3 661 and Scotland accounted for 158. To-day the membership of the Institution is 11 315, of which the Scottish Centre accounts for 652. These figures are a very striking commentary on the growth of the parent Institution during a single generation. Not only so, but the original name of "Telegraph Engineers" indicated the only real commercial use of electricity at that date. How shall we compare it with our present title of "Electrical Engineers," and with the fact that the latest issue of a Trades Directory contains no fewer than 975 distinct trade headings, from which we may gather that there are just so many distinct or partially distinctive ramifications in the industry as at present constituted?

The importance to the community at large of the electrical industry—and of this Institution in particular—has been recognized by the highest authority in the land. We are now incorporated by Royal Charter and thus enabled to use the designation of "Chartered Electrical Engineer." This is a privilege of which we may well be proud, both as individual members and as an Institution which is representative of the scientific and technical development of the industry. With the privilege comes the added responsibility to maintain the Institution always in the forefront of progress and so make its future history worthy of its past record and of the best traditions of our race.

The development of the electrical industry, looked at from the financial aspect, has been phenomenal during the years that the Institution has been in existence. It is always difficult to ascertain exactly all the capital invested in any industry at any given time, but it is fairly safe to assume that it is proportionate to the amount invested in public companies. If we compare the figures for 1922–3 with those of 1897 we find that the capital invested in the latter year was only one-tenth of that in the former, the actual amounts in round figures being:—

	Total invested capital
1897	£68 000 000
1922–3	£650 000 000

These figures include supply, manufacturing and distributing concerns, and also include the loans authorized to municipal electric supply undertakings. In addition to this, there is the capital sunk in private businesses, which must amount to a very large sum in the aggregate.

No figures seem to be available of the number employed in the electrical industry. It is computed—though I cannot vouch for its accuracy—that the number of workers directly engaged in electrical manufacture and distribution is somewhere approaching 250 000. This I can believe, as one manufacturing company alone numbers its employees in tens of thousands. Truly this is an industry in which we ought all to feel a glow of pride, more especially as this development has taken place within our own lifetime and before our own eyes.

The growth of electrical science has been even more striking and, in many ways, has a distinct suggestion of romance. As I write I have before me a thin, tattered, old volume entitled, "Lectures on Electricity, by James Ferguson, F.R.S., a new edition, corrected, with an Appendix adapting the work to the present state of science," by C. F. Partington, and it is dated 1825. It was bought for a few coppers from an old book-barrow in a Glasgow street, but its value to-day,

is not measured by its tattered cover, its faded pages, or its actual cost. It is a milestone on the march of progress, and its line drawings and quaint phraseology are at once incentive to us towards further endeavour, and a warning not to decry or belittle the day of small things. This little volume is devoted exclusively to descriptions of apparatus for producing static electricity and to experiments which could be performed with the globe, cylinder and plate machines. We learn, for instance, that 30 square feet of coated surface distributed over a number of "Leyden phials" will "fuse the greater part of two feet of wire one-fiftieth of an inch in diameter." It is a very far cry from those small condensers to the large industrial condensers of to-day, for power factor improvement, which can deal with thousands of kilowatts.

We need not go back 100 years, however, to discern the huge advances which we have made in scientific knowledge. The professor whose junior assistant I was at an early stage of my electrical career airily dismissed alternating currents from his lectures by the casual remark that there were one or two central stations giving such a supply, but it was only a fad which would soon die a natural death! He has long since crossed the great divide, but alternating-current supply is not yet dead; it is daily running more and more of the world's business and pleasures.

The growth of scientific knowledge at once renders it necessary to provide greater facilities for study, and the way in which our technical colleges have expanded is ample evidence of the changes that have taken place during the past 30 years. Many of you can remember, as I do, when the technical institution of this city had to be housed in three different buildings, all inadequate. We had the College of Science and Art, 38, Bath-street, and the Andersonian College, in George-street, and the overflow classes from both buildings were held in some of the rooms in Allan Glen's School. Some of us had to be in two places on the same evening. The class-rooms were cramped and badly lighted, the laboratory accommodation was extremely limited, and the apparatus was excessively crude compared with present-day standards. In spite of, or perhaps because of these disadvantages, there was a keen body of students who put heart and soul into their work and studies. Many names which are now well known and looked up to in their respective spheres were inscribed on the roll of students in those days. Times have changed and the magnificent building which now houses the Royal Technical College covers the site of the old Andersonian and many adjacent sites as well. Its laboratories are fully equipped, not only with the finest measuring instruments, but with full-grown machinery and apparatus very unlike the toy gear we had to work with in our student days.

I sincerely hope that the youth of our city and neighbourhood appreciate the advantages that they now enjoy, and that the result may be to incite them to keener study and a greater devotion to the cultivation of scientific research.

When Glasgow Corporation took over from Muir, Mavor and Coulson the electric power station in John-street, and so became electricity undertakers for the city, the largest single unit in use was one of 80 h.p., equivalent to 60 kW. That was in 1892; to-day the largest single unit in the Dalmarnock power station is of 25 000 h.p., equivalent to 18 750 kW—another indication of the march of progress.

The growth of the Clyde Valley Power Company has been just as striking. In the opening year, 1905–6, the largest unit was 2 000 kW; now this has given place to units of 21 000 kW. The total capacity of the plant in 1905–6 was only 4 000 kW; to-day it is 87 500 kW, with a further 20 000 kW of steam plant and 15 000 kW of water-power plant on order.

The total capacity of the Glasgow Corporation plant in 1892 was 270 kW, whilst now 150 850 kW is available. Just think of it for a moment—the original capacity multiplied 560 times in the space of 32 years. What will be the increase in the next 20 or 30 years? From the accompanying table it will be seen that the plant capacity has been trebled in the last 10 years, while the units generated have increased about 120 per cent.

Growth of Glasgow Corporation Electric Supply Undertaking.

Year	Net capital expenditure, less depreciation	Gross revenue	Capacity of plant installed	Units generated	Coal per unit generated
	£	£	kW		lb.
1893	96 697	7 784	360	408 529	20·23
1904	1 119 048	158 190	13 950	17 770 488	5·23
1914	2 456 782	378 315	54 787	92 286 953	3·41
1924	7 068 472	1 153 194	150 850	205 874 443	1·89

This table is interesting in another respect. The last column gives the number of pounds of coal consumed per unit generated. In 1893 it required 20·23 lb. to produce a unit of electricity at the switchboard. To-day this figure has been reduced to 1·89 lb., less than one-tenth of the amount used 30 years ago.

We seem now to be approaching the limit of reduction in fuel consumption, as an increase in the number of units generated gives us only a fractional advantage, and I fear, therefore, that we can look for cheaper electricity only when we have discovered some more revolutionary method of producing it. This brings me to a matter of immediate and material interest to us all: How to increase and develop the domestic load?

I remember quite well a period, not so long ago, when the Electricity Department discouraged the use of electric heating and cooking appliances in private

houses. That was a passing phase due to overloaded mains and out-of-date distribution. The provision of high-tension feeder cables and district substations paved the way for a campaign to increase the domestic load. For some years now a good deal of encouragement has been given to the use of heating and cooking appliances, and yet we have only touched the fringe of the possible business to be done. Not only is there a heating and cooking load to be worked up, but there is an even greater lighting load absolutely untouched, awaiting development. It is calculated that there are more than 8 million houses in Britain without electric light, equivalent to an annual load valued at £49 000 000, and each of these houses when once supplied with current is a potential user of heating and cooking gear as well as light.

I think that it is wise, therefore, to consider why the results so far obtained have been so meagre, compared with the energy expended in advertising, canvassing and demonstrating. There would seem to be several reasons for this state of affairs:—

(1) The installation cost has scared off a great many likely users.

(2) The first cost of cooking appliances is high, much higher than that of corresponding gas-heated devices.

(3) The cost of electrical energy is still in many cases too high.

(4) The method of charging for energy supplied is often too complex for the comprehension of the average consumer.

As there is no intention in this address to go deeply into detail I shall content myself with a few general observations on these points.

(1) *Installation costs.*—In a city such as ours, where the great majority of the possible users are resident only in rented premises, the question of the cost of an installation assumes an importance altogether out of proportion to its intrinsic importance. Whenever electric wiring is installed in a house or shop or office, it at once becomes automatically part of the building and, as such, passes out of the ownership of the occupier who has the use of it only during his tenancy. Consequently, costs which may be quite reasonable in themselves assume an entirely different aspect when looked at from the point of view of a tenant with uncertain tenancy. The introduction of electric lighting into any premises enhances their value, and it seems unreasonable that the outgoing tenant should not be recompensed by the proprietor for such an obvious improvement. If the tenant farmer finds it necessary to build a dyke round his piggery he can claim against his landlord for this improvement, while for a similar case the city dweller may not—either an injustice to the latter or a gratuitous pampering of the former.

The scheme recently introduced by Glasgow Corporation, whereby the proprietors and tenants (with the backing of the Electricity Department) share in the cost of installation, appears to be a step in the right direction. Here, the proprietor pays for the main cabling, whilst the tenant pays by instalments for the wiring of his own house. It is manifestly unfair to ask the tenant on the third floor of a tenement to pay for mains from the street-level; that is the proprietor's duty, and his alone. Personally I am of opinion that he should also pay at least a proportion of the cost of the internal wiring. He gets that extra value added to his property and I can see no reason why a property owner should receive presents of this nature. The Glasgow scheme has now been in operation for three months and the results to date have been sufficient to warrant confidence in its success.

(2) *Cost of apparatus.*—From the very nature of electrical appliances, compared with gas cookers and heaters, there must be a great difference in first cost, and it is our duty frankly to acknowledge such a basic fact. Our contention should be that the convenience, comfort, cleanliness, economy and safety of the electrical apparatus so far exceed those of the rival gear that the extra expenditure is fully warranted and will be repaid with interest during the useful life of the appliances. I am pleased to notice that the cost of good-quality gear is steadily decreasing. Increased production due to increased demand, coupled with standardization and simplification of design, should lead to further reductions, and I hope that we may soon see an electric cooker placed on the market at a price within reach of the proverbial "million."

Our Electricity Department within recent years organized a very popular hire system. It is possible to have various opinions on this method of creating increased demand for energy. If the cost of upkeep of the apparatus, added to the interest on invested capital and a proper amount for depreciation, can all be covered by the annual hire payment, then everything is all right. On the other hand, if such is not the case and the hiring results in a loss which is made up by the price charged for the current, then this method is wrong. There is no reason whatever why one person should be given a too cheap electric cooker service while every other user of current has to make up the loss involved in doing so.

The hiring scheme in Glasgow has been a great success and has exceeded all expectations. There are now approximately 1 100 electric cookers and 3 500 radiators let out on hire to consumers on the system.

(3) *The cost of energy.*—This is a very large subject and a most vexatious one to deal with, for it at once introduces complicated factors in connection with not only the generation but also the distribution and use of electrical energy.

The increase in the size of generating units has resulted in a decrease in the generating costs, and the figures in the table already referred to, showing the number of pounds of coal per unit generated in the Glasgow stations, is instructive, as showing the economies effected during the last few years. In this connection it is of interest to note that the Report of the Electricity Commissioners places the Glasgow stations at the head of their list for thermal efficiency, and the Clyde Valley figures are not far behind.

High-tension distribution to local substations from which there radiates a compact system of distributors is reducing the losses in that part of the system. It would appear, however, that the cost of distribution

is still too high, being much in excess of the cost of generation, and supply engineers will have to concentrate their efforts in effecting reductions in this direction.

No supply undertaking is, however, capable of controlling the manner in which the energy is used by the consumer. This is where the contractor can do a lot of useful work. By planning an educational campaign for the benefit of his clients, by instructing them as to the most economical lamps and apparatus to use and how to get the best results at the least expenditure, their bills will be reduced, with the ultimate result that the same people who now grumble at their electricity bills will install more consuming devices, because they will realize that they are getting efficient apparatus and good value for their money.

In this work the contractor might get a good deal of assistance from the British Electrical Development Association, which issues literature intended primarily for the consumer's education. The fact that we now have such an organization is a further sign of progress. To make this body of greater service to the industry as a whole, it is obvious that it needs the whole-hearted support of the supply, manufacturing and contracting interests. A very fine exhibit at Wembley Exhibition arranged and controlled by the Association must have brought home to millions the convenience, utility and comfort of electric light and power.

The cost of energy to the consumer is not merely the rate per unit charged by the supply undertaking, but is also the cost to him of inefficient apparatus and faulty use. It would pay both the suppliers and the contractors to reduce this cost as far as possible, for a satisfied customer is the very best advertisement which it is possible to have.

(4) *System of charging.*—The varied and, in many cases, complicated systems in use for charging for the supply of electrical energy have certainly not done anything to popularize the use of electricity, and I am very pleased to see that there is now a decided tendency to leave mathematical methods severely alone and give a simple straightforward tariff.

For domestic supply, while the maximum-demand tariff is still used by both the large supply authorities in our area, they are now giving an alternative rental method which involves a flat rate for all units recorded on the meter. This rental system consists of two parts: (1) a fixed annual charge and (2) a flat rate per unit as recorded on the meter. In one instance, for example, the fixed annual charge is based on the size of the house, being 20s. per room; and in another the fixed charge is equal to approximately one-eighth of the house rent. The flat rates per unit vary from $\frac{3}{4}$d. to $\frac{1}{2}$d. per unit recorded on the meter.

A comparison of two typical residential areas shows that where the maximum-demand tariff is in operation the average price per unit is 3·1d. and the average income per consumer is £6 1s. 6d., whilst where the rental tariff is in use the average rate per unit is only 1·39d., but the income per consumer is on the average about £14.

Many consumers who use electricity for cooking and heating throughout get their supply for much less than this figure, the rate per unit in some cases falling as low as 0·915d. Figures such as these would suggest that a simple understandable method of charging will assist in raising the domestic demand to a much higher level than the station engineer has yet conceived. This new era will not arrive, however, unless we work for it.

As a contractor, I would address a few words especially to the contractor members of the Institution. The association between the contractors and the Institution should be closer than it is at present. The Institution is democratic, and as such welcomes the contractor as a member, and he should take his place and make his presence and interest felt. For many reasons the Institution is well worthy of all the support the contractors can give it. To instance two or three only: There is the National Scheme of Registration, and the issue of Wiring Regulations for the Electrical Equipment of Ships and also Buildings.

For years a Committee of the Institution studied and discussed the registration question, and finally evolved the scheme now in force, a scheme which is attracting the contractor in increasing numbers and which is undoubtedly raising his status.

The Institution Wiring Rules issued many years ago have now been re-drafted and their scope widened, and they are now termed Regulations for the Electrical Equipment of Buildings. The present issue is the Eighth, dated June 1924. This is good work for the community and for the contractor. Some are inclined to suggest that we have too many regulations and too many laws, but just as the honest man can walk without fear of the law so the honest contractor has no quarrel with regulations designed for the good of the industry. I think that, for these reasons alone, the contractor should support the Institution to the utmost.

Now to drive home a moral. We all look forward to the time when electric cookers, radiators, vacuum cleaners and so on will be as plentiful and commonplace as autumn leaves in the forest. What are we doing to help? How many in this room have their meals cooked electrically at home? How many radiators have you? Is your electric lighting carried out on modern scientific lines? If we do not set the example ourselves, how can we expect others to do what we merely advise? It is, therefore, most essential that we should first set the example, so that others may follow.

EAST MIDLAND SUB-CENTRE: CHAIRMAN'S ADDRESS

By T. R. SMITH, Member.

"THE NEW LEICESTER CENTRAL GENERATING STATION."

(ADDRESS *delivered at* LOUGHBOROUGH, *7th October*, 1924.)

It has been a matter of some concern to me to select a suitable subject for my address, but I feel that perhaps I cannot do better than give some particulars of the new Leicester central generating station, the design and construction of which has been my principal task during the past three years.

The station is still in course of construction, but I propose that my remarks shall fall into three distinct sections, as follows:—

(1) A general description of the work at present in hand, or completed.

(2) Particulars of the general performance of that portion of the plant which is at present in operation.

(3) Some discussion of the lines on which the future development of the station may take place.

(1) GENERAL DESCRIPTION OF WORK IN HAND, OR COMPLETED.

The Leicester central generating station was designed for an ultimate plant capacity of 65 000 kW.

Site.—This is adjacent to the River Soar, the subsoil consisting of gravel and marl with a layer of shale at a depth of 9 ft. capable of carrying the foundations of plant and buildings.

The river widens out into two large basins opposite the site, separated by a weir 500 ft. in length. In time of dry weather circulating water is drawn from the lower basin and discharged above the weir, but when there is a large quantity of water coming down the river the water is returned to the lower basin.

The London Midland and Scottish Railway runs along the southern boundary of the site and coal can therefore be delivered by either rail or barge.

Buildings.—The portions at present erected are No. 1 boiler house, the turbine room and annex to a point between Nos. 2 and 3 turbines and a portion of the e.h.t. switch-house. The whole of the buildings, with the exception of the e.h.t. switch-house, are of steel-framed construction, the concrete foundations for the stanchions extending down to the shale.

The turbine house is 159 ft. long and 42 ft. in span between the crane rails, the basement floor being at the site level and the turbine floor and the eaves of the turbine room being respectively 20 ft. and 46 ft. above the basement floor. The annex to the turbine room is 19·5 ft. wide and has four floors, viz. the workshop floor, the low-tension control-room floor, the high-tension control-room floor, and the tank-room floor.

The circulating-pump chambers adjoin the turbine room annex; they are 15·25 ft. below the basement level and the pumps are totally immersed at all times.

The boiler house is 152·5 ft. long by 87·75 ft. wide, the basement being at the same level as that of the turbine room. The basement contains the forced-draught fans and duct, the stoker motors with reduction and driving gear, and is so arranged that special ash wagons of 4 ft. 8½ in. gauge can be run in directly beneath the boiler ash hoppers.

The firing floor is 12 ft. above the basement and carries the induced-draught fans in addition to the boilers. The coal supply to the boilers is taken from steel bunkers, the total bunker capacity being 1 000 tons.

The high-tension switch-house is 133·5 ft. long by 24 ft. wide. The ground floor accommodates concrete cubicles which house the oil switches, the feeder isolators, the instrument and protective transformers and the current-limiting reactances. The first floor, which is 12·5 ft. above the ground, contains the busbar chambers with busbar isolators.

A cable tunnel 7 ft. deep by 8·5 ft. wide runs the entire length of the switch-house and is continued into the main turbine room.

Coal-handling plant.—The bulk of the coal used is delivered by rail into the sidings on the bank at the southern side of the site. Trucks are weighed and drawn by locomotive or capstan into the tippler on the embankment. The tippler, which has automatic clamping gear, discharges the coal on to the long conveyer. The coal is then either moved to the overhead bunkers by means of cross-conveyer and skip hoist or placed on the storage heaps by means of the small movable distributing conveyer, which can be moved to any position throughout the length of the long conveyer.

The conveyers consist of rubber belts running on ball-bearing idlers, are driven by back-geared three-phase motors at a speed of 360 ft. per minute and are capable of handling 120 tons of coal per hour. The skip hoist has a similar capacity to the conveyers and is entirely automatic. A 3-ton grab on an electric level luffing travelling crane is used for reclaiming coal from the storage heap. The reclaimed coal is placed into a movable hopper which feeds it on to the long conveyer, from whence it passes up to the bunkers via the cross-conveyer and skip hoist.

Ash plant.—The ashes are discharged over the ends of the chain-grate stokers into steel-framed ash hoppers, where they are quenched by water sprinklers fixed in the upper portion of the hoppers. The hoppers discharge by means of sliding valves into special ash wagons in the basement.

Boilers.—The boiler house contains eight steel-cased boilers, four Babcock boilers and four Spearing boilers.

The Babcock boilers are of the well-known cross-drum, marine type, with integral superheaters, and "tritube" superposed cast-iron economizers. The heating surfaces of the boiler, superheater and economizer are respectively 6 948 sq. ft., 2 368 sq. ft. and 4 435 sq. ft. Each Babcock boiler is equipped with three Babcock chain-grate stokers 16 ft. long by 6 ft. 6 in. wide, giving a total grate area of 312 sq. ft. per boiler. Each stoker chain is driven by a worm, four-speed gear-box and chain from a shaft running the entire length of the boiler-house basement. The shaft is divided by dog clutches into four sections which can be coupled together at will, and each section of shafting is coupled by means of a chain and worm reduction gear to a 6-h.p. motor running at 950 r.p.m. Six stokers may be driven by any one motor. The forced-draught fans, three in number, are situated in the basement and discharge into a common duct running the length of the boiler house. Three 40-h.p. motors running at 360 r.p.m. are direct-coupled to the three forced-draught fans, and any two fans are capable of supplying the needs of all four boilers. An induced-draught fan driven by a 46-h.p. motor at 410 r.p.m. is provided for each boiler on the firing floor level, and is capable of dealing with the gases from one boiler only. The Babcock boiler plant is designed for a duty of 45 000 lb. of steam per hour per boiler, at 275 lb. per sq. in. (gauge) and 700° F. total temperature, with feed at 180° F. and coal of 8 000 B.Th.U. (lower net calorific value as fired). The coal most generally fired gives on test the following results:—

Lower net cal. value (212° F. exit temp.)	=	9 330 B.Th.U./lb.
Total moisture, per cent ..	=	13·7
Volatile (as fired), per cent	=	29·0
Ash (as fired), per cent ..	=	15·7

and with this fuel the above duty is easily obtained.

The Spearing boilers are at present in course of erection and are of the double-drum type with special downcommer pipes. Integral superheaters and superposed "tritube" cast-iron economizers are embodied. The heating surfaces of boiler, superheater and economizer are respectively 7 590 sq. ft., 2 300 sq. ft. and 5 200 sq. ft. These boilers are rated similarly to the Babcock boilers and the general arrangement of their auxiliaries is somewhat on the lines adopted for the Babcock boilers, with the exception of the stokers and forced-draught fans. The stokers are of the Illinois type, and one stoker 16 ft. long by 18·5 ft. wide is provided for each boiler. These stokers are driven by a worm gear-box and chain from a shaft in the basement, as in the case of the stokers previously described. A forced-draught fan driven by a 32-h.p. motor at 410 r.p.m. delivers air into two wind-boxes one on either side of the stoker, from whence the air passes through dampered openings into eight compartments running transversely beneath the stoker chain. This arrangement enables the quantity of air passing through the grate over any compartment to be adjusted according to the requirements of the fire bed at that point, and results in a better CO_2 figure than can be obtained with the non-compartmented type of stoker.

Steam ranges.—Each line of four boilers feeds into a separate receiver, the two receivers being interconnected by a 12-in. pipe. The steam range connecting with the Spearing boilers has been carried overhead in order to secure the maximum flexibility and thereby to reduce temperature stresses to a minimum. It is hoped that this will possess marked advantages over the earlier range which is situated in the basement.

Feed-ranges.—These are constructed of cast-iron pipe with steel bends. The arrangement enables either set of boilers to be supplied from either the steam or electric feed pumps. A master Venturi meter measures the total feed supplied to either of the two main feed-ranges, and Venturi meters are also placed between individual boilers and the range. The feed to all the boilers is controlled by automatic regulators. The whole of the make-up feed water is taken from an evaporator, and the arrangement of the feed system has proved most satisfactory.

Turbine plant.—There are two main turbo-alternators and one small turbo-alternator for house-service purposes. No. 1 turbo-alternator has a maximum continuous output of 10 000 kW at 1 500 r.p.m., with an overload capacity of 25 per cent for two hours.

The terminal conditions of this machine are as follows:

Voltage	6 600
No. of phases	3
Frequency	50 periods per second
Steam pressure	250 lb. per sq. in. (gauge)
Steam temperature ..	700° F.
Vacuum	28·7 in. (bar. 30 in.)
Circulating water inlet temp., 65° F.	
Circulating water outlet temp., 78° F.	

With these terminal conditions the machine consumes 10·6 lb. of steam per kWh at full load, exclusive of the steam consumed by the ejectors. The turbine is of the impulse type having 10 pressure stages and two velocity stages in the first pressure stage. The nozzles of the first pressure stage are divided into three groups, each group being controlled by an automatic valve, the nozzle area being varied to suit the load conditions. A surface heater takes steam from a point immediately in front of the sixth stage of the turbine, heating the main condensate as described later.

The alternator is of the usual type with a closed air circuit and air cooler. The rotor is a solid steel forging carrying fans at either end. The exciter is carried on an extension of the main bedplate and is driven from the end of the alternator shaft by means of a pin coupling.

The condenser, which is supported on springs, is bolted direct to the turbine exhaust flange and has a total cooling surface of 17 750 sq. ft. Duplicate plant is provided for extracting the air, either by steam-jet ejectors or a rotary kinetic air pump. The pumps for extracting the condensate are also in duplicate.

No. 2 turbo-alternator has a maximum continuous rating of 12 500 kW at 3 000 r.p.m., with no overload guarantees. The terminal conditions under which this machine operates are exactly the same as those for

No. 1 turbo-alternator, and under these conditions the full-load steam consumption is 10·72 lb. per kWh, and at a load of 10 000 kW the consumption is 10·37 lb. per kWh.

This turbine is of the impulse type with 7 pressure stages, a hand-operated valve being arranged to by-pass the first wheel on overload. The alternator for this machine is of the two-pole type with the exciter armature carried on an extension of the shaft over-hung from the outboard bearing.

In design and construction this machine is very similar to No. 1 alternator. The condenser has a total cooling surface of 17 800 sq. ft. and is supported and connected to the turbine exhaust in a similar manner to No. 1 condenser.

The air-extraction plant and the condensate-extraction pumps are both in duplicate, the air extraction being carried out entirely by steam ejectors.

Condensate and feed heating systems.—The condensate from both main generating sets unites into a common stream after it has passed through the Venturi tubes, flowing through the surface heater of the house-service set and the bleeder heater of No. 1 main set direct to the boiler feed pumps.

The surface heater utilizing the exhaust of the house-service set and the heater utilizing bled steam from No. 1 main set can be by-passed. The condensed steam from the house-service set is extracted by means of a small pump which feeds it into a drip tank. The drip tank also serves as a collecting tank for all clean-water drains in the station. The contents of the drip tank are returned to the main condensate stream by means of a small pump. No hotwells are provided, any inequalities in the rates of flow through the feed pumps and the extraction pumps being balanced by a surge tank in the annex. The surge tank also gives storage capacity and receives any make-up that is necessary from the evaporated-water storage tank, which is also in the annex. It is to be noted that complete control of the feed temperature is obtained by varying the load on the house-service set, or by varying the amount of steam bled from No. 1 main turbine.

Circulating water system.—Water may be taken in at two points below the weir and discharged above the weir, or in times of flood it may be both taken in and discharged below the weir. Two motor-driven circulating pumps in chambers adjacent to the turbine room annex supply water to each main condenser. They are totally immersed at all seasons and each pump is capable of supplying half the amount of water required by the condenser when on full duty.

Drive of auxiliaries.—With the exception of the feed pumps, all the auxiliaries are electrically driven from a three-phase, 50-period supply at 415 volts. Energy for driving the auxiliaries is obtained either from the house-service set of 500 kW capacity or from two 1 000-kVA transformers, stepping down from 6 600 volts to 415 volts.

The house-service set is usually in parallel with the auxiliary transformers and operates at a vacuum varying from 10 to 23 in., according to the load on the main sets, but in cases of emergency the house-service set is used exhausting direct to atmosphere.

Feed pumps.—There are four boiler feed-pumps, each pump being capable of delivering 25 000 gallons of water per hour against a pressure of 320 lb. per sq. in. The temperature at the feed-pump suctions is normally 180° F. and there is a pressure head of 23 ft. on the suction side. Two of the pumps are steam-turbine-driven and two are driven by 135-h.p. electric motors. The turbines of the steam pumps are arranged to exhaust into the surface heater of the house-service set.

Main e.h.t. switchgear.—The station will eventually have four main sections of e.h.t. busbars with a reserve busbar and a set of reactance tie-bars. At present there are two main sections of busbars, with reserve bars and reactance tie-bars. It is possible to connect the main busbar sections directly together by means of a section switch, or to connect them together through reactances and the tie-bars. It is also possible to connect either of the main busbar sections in a similar manner to the reserve busbars. By suitable arrangement of the isolating switches it is possible to connect a generator or feeder to either the main busbar section or the reserve busbars. Each of the main oil switches has a rupturing capacity of 500 000 kVA, and the reactances are so proportioned that the worst fault will give a short-circuit current within the rupturing capacity of the oil switches.

(2) General Performance.

The performance of the station under normal conditions for the period 8th September to 22nd September, 1924, is given below.

Period under observation ..	336 hours
Steam pressure	251 lb. per sq. in. (gauge)
Steam temperature ..	692° F.
Vacuum (bar. 30 in.) ..	28·4 in.
Temperature of feed water	168° F.
Total heat of steam from feed temperature ..	1 223 B.Th.U./lb.
Coal.	
Calorific value of dried sample	11 304 B.Th.U./lb.
Lower net calorific value (212° F. exit temperature)	9 300 B.Th.U./lb.
Moisture	13·26 per cent
Volatile (as fired)	29·07 per cent
Ash (as fired)	15·56 per cent
Evaporation.	
Weight of coal consumed ..	1 608·4 tons
Weight of water evaporated	21 679 800 lb.
Weight of ash made ..	246·3 tons
Weight of water evaporated per lb. of coal	6·02 lb.
Boiler efficiency based on lower net calorific value..	79·2 per cent
Boiler efficiency based on coal of 9 850 B.Th.U./lb.	74·7 per cent
Station output.	
Units generated	1 551 300
Units sent out	1 475 020

Units used on works ..	76 280
Maximum generator load ..	10 800 kW
Weight of coal per unit generated	2·32 lb.
Weight of coal per unit sent out	2·44 lb.
Overall station efficiency based on units sent out and lower net calorific value	15·0 per cent
Overall station efficiency based on units sent out and coal of 9 850 B.Th.U.	14·2 per cent

The plant in service during the period under observation consisted of No. 1 turbo-generator (normal rating 10 000 kW), and three Babcock boilers each rated normally at 45 000 lb. evaporation per hour from feed at 180° F. to steam at 275 lb. per sq. in. (gauge) and 700° F. total temperature.

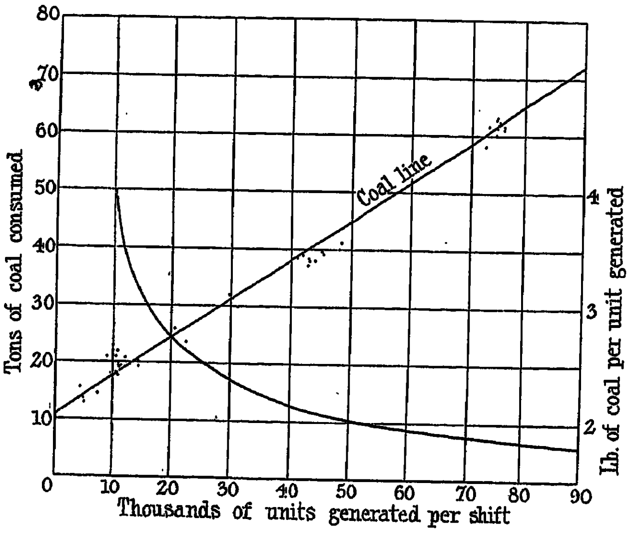

FIG. 1.—Coal line.

$C = 24\,600 + 1\cdot515\,K_g$

where C = coal consumption in lb. per 8-hour shift (10 000 B.Th.U. lower net calorific value; exit temperature, 212° F.);
K_g = units generated per 8-hour shift.

The plant had been in commercial service for a period of 22 months when the readings were taken, and during the period under observation it was operated under normal station conditions. It should be noted that no special boiler-cleaning had taken place before the test.

Special note should be taken of the coal used. This is a fine slack of inferior quality, the moisture, volatile and ash contents being high, while the carbon content is particularly low.

In order to facilitate comparisons between the performance of this station and others working under different conditions of load factor the results have been plotted in the form of Parsons lines based on coal at 10 000 B.Th.U. per lb. lower net calorific value (212° F. exit temperature). Fig. 1 shows the coal line per shift, and Fig. 2 the steam line per shift, while Fig. 3 shows the evaporation line.

Coal line.—Fig. 1 connects the coal used during any 8-hour shift with the units generated. The equation of this curve is $C = 24\,600 + 1\cdot515\,K_g$, and therefore

$$E = \frac{24\,600}{K_g} + 1\cdot515$$

where C = weight of coal in lb. per 8-hour shift,
K_g = units generated per 8-hour shift, and
E = coal consumption per unit generated (average).

From these equations, or from the curve, it is possible to predict the coal consumption per shift for any electrical output, and it will be noticed that the constant

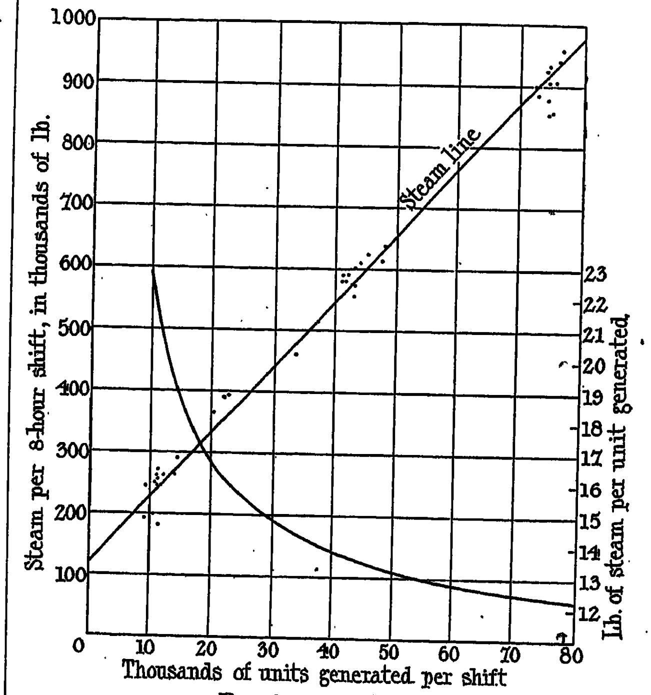

FIG. 2.—Steam line.

$S = 120\,000 + 10\cdot75\,K_g$

where S = lb. of steam per shift;
K_g = units generated per shift.

24 600 represents the weight of coal in lb. required to keep the station running at no load. It is seen that 1·515 lb. of coal per unit generated corresponds to the limiting thermal efficiency of the station, which would theoretically be 22·5 per cent. The actual overall thermal efficiency on full load is 18·75 per cent.

Steam line.—Fig. 2 shows the steam consumption during any 8-hour shift, plotted against the units generated. The equation of this curve is $S = 120\,000 + 10\cdot75\,K_g$

from which $$U = \frac{120\,000}{K_g} + 10\cdot75$$

where S = total steam consumption in lb. per shift,
U = steam consumption in lb. per unit generated, and
K_g = number of units generated.

The quantity S includes the steam used by the boiler feed-pumps, two battery storage locomotives used in connection with the coal and ash plant, and steam used for heating offices, mess rooms, etc. The constant of 120 000 lb. represents the amount of steam which must be generated during every 8-hour shift in order to keep the station running on no load. The figure of 10·75 lb. is the limiting steam consumption of the station. This would be reached when the output had reached such magnitude as to render the no-load losses insignificant. This is equivalent to a limiting thermodynamic efficiency of 72·4 per cent.

Evaporation line (Fig. 3).—From the foregoing equations it follows that:—

$$C = 7\,730 + 0{\cdot}141\,S \qquad S = 7{\cdot}1\,C - 54\,800 \qquad E = 7{\cdot}1 - \frac{54\,800}{C}$$

where E = evaporation in lb. of steam per lb. of coal,
S = steam generated per 8-hour shift, and
C = coal consumed per 8-hour shift.

The constant 7 730 is the weight of coal in pounds required to maintain the boilers at full pressure when

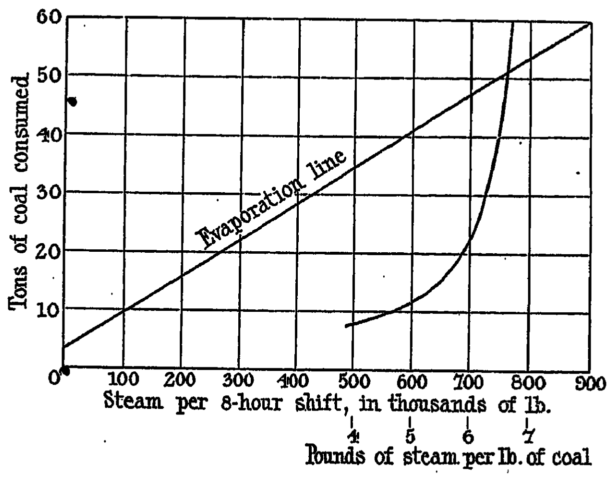

FIG. 3.—Evaporation line.
$C = 7\,700 - 0{\cdot}141\,S$
where C = lb. of coal per shift (10 000 B.Th.U. lower net calorific value);
S = steam per shift.

the station is at no load—in other words the banking loss—and by subtracting this quantity from 24 600 the constant no-load heat loss of the turbine room is obtained. It is therefore seen that the boiler-house no-load heat loss is equivalent to 3·45 tons of coal per shift and the turbine-room no-load heat loss to 7·55 tons of coal per 8-hour shift.

The limiting boiler-house efficiency corresponds to 7·1 lb. of steam per lb. of coal, or 86·9 per cent. It is felt that this performance is fairly creditable having regard to the low-grade fuel used. During the period under review the lower net calorific value varied between limits of 8 750 B.Th.U. and 9 820 B.Th.U., the ash (as fired) between 13 per cent and 21·3 per cent and the moisture between 11·4 per cent and 14·9 per cent.

Considerable trouble was experienced when the station was first put into commission, due to lack of uniformity of the fire bed, the nuts and peas tending to separate from the fine coal. After much experiment with baffles in the coal chutes from the bunkers this trouble was practically eliminated. Our next trouble was a tendency of the fire to burn thin down one side of each grate, greatly upsetting our CO_2 figures. This has recently been remedied by a special arrangement of baffling in the ash pits; this produced an immediate improvement of 1½ per cent in the CO_2 figures. We are at present experimenting with varying designs of arch and I have every hope that we shall be able to show an improvement on our present boiler-house efficiency in the course of a few months.

When non-compartmented stokers are used to burn a coal of high moisture and ash content, great difficulty is experienced in burning out the ash with a reasonable amount of excess air. This is our great difficulty with the present Babcock stokers and we find it necessary to take ash samples for each shift with as much care as we expend on coal sampling, keeping careful watch on the percentage of unburnt carbon in the ash.

The boilers nearing completion are equipped with compartmented stokers and it is hoped that we shall have much less trouble in dealing with low-grade fuel on them.

(3) FUTURE DEVELOPMENT.

In order to bring the station up to its ultimate capacity there still remain three 15 000-kW generating units and another boiler house of equal capacity to the existing house to be installed, together with switchgear and auxiliaries. The switchgear is bound to follow the scheme which has been prepared, of which the present gear forms a part. It can also be predicted with certainty that all the auxiliaries will be electrically driven, thus leaving greater possibilities in regard to bleeding the main units for feed-heating purposes. The main 15 000-kW turbo-generators will operate at 3 000 r.p.m. and, though there would be an increase in the available heat-drop and therefore in the limiting station thermal efficiency due to an increase in boiler pressure, I am inclined to think that it will be necessary to retain our present pressure in the interests of flexibility. I also feel that the present steam temperature of 700° F. cannot be exceeded without involving serious maintenance costs.

We shall do as much bleeding from the main sets as possible, but the amount of bleeding will depend very much on the policy adopted in the boiler house. The boiler house presents an absorbing problem. The rate of advance in the design of steam-raising plant is greater now than at any previous period and we have to consider the claims of low-temperature carbonization with by-product recovery of pulverized fuel, and mechanical stokers. Our particular circumstances will, I think, enable us to dismiss the former and turn our attention to the rival claims of pulverized fuel and stokers. The problem is simply which of these two systems will economically give us the higher percentage of CO_2, the lower flue-gas temperature and the lower ash pit loss, with a given feed temperature. From past experience,

I am inclined to think that my next boiler specification will not call for an efficiency guarantee. I shall ask for a guarantee as to CO_2, flue-gas temperature and unburnt carbon in the ash, with fuel of a given ultimate analysis and feed at a stated temperature. These figures govern the chief losses and are easily obtainable.

With the present pressure the temperature of the gases leaving the boilers is more or less fixed at, approximately, 550° F. for both pulverized-fuel and stoker plant, and in both cases some method of securing a reduction of this temperature has to be devised. At present, the usual practice in this country is to provide extra cooling surface in the form of economizers through which the feed water is pumped. With economizers it is economically possible to get the gases down to 375° F., thereby reducing the chimney loss to approximately 14·2 per cent with the feed temperature about 160° F. If the temperature of the feed is increased the efficiency of the economizer is reduced, and it will be seen that the use of economizers places a limit on the amount of bleeding that can be done from the main turbine.

There are two great streams of waste heat from a power station, viz. the heat wasted up the chimney and the heat wasted in the circulating water, and we can only hope for any considerable improvement in efficiency by absorbing heat from these two streams. The only way of recovering heat from the circulating-water stream is by bleeding the main turbine as much as possible. This therefore causes us to look for means other than the economizer for reducing the temperature of the gases after they leave the boiler, and it at once becomes apparent that an efficient system of extracting the heat from the flue gases and imparting it to the air entering the furnace is extremely desirable. There are various practical difficulties in the design of air heaters, but it is possible theoretically to design a heater which would reduce the flue gas temperature to 375° F., thereby obtaining a boiler efficiency equal to that obtained with economizers.

Turning now to the effects of bleeding the main turbine, and assuming the turbine to be bled at one point only, the thermodynamic efficiency being 75 per cent, it can be shown that the heat-conversion coefficients of the plant with feed heated to 160° F. and 330° F. are 0·351 and 0·3705 respectively. The plant with feed heated to 330° F. would therefore consume approximately $5\frac{1}{2}$ per cent less coal than the plant with feed at 160° F., provided always that the flue-gas temperature attained with the air heaters was as low as that attained with economizers. It can therefore be taken for granted that if air heaters are a practical proposition when the next boiler extension takes place, we shall certainly install them with extensive bleeding of the main turbines. The bleeder heaters will of course be on the pressure side of the feed pumps. The use of an air heater will of course render the links of chain-grate stokers more liable to burn out, but this is one of the difficulties which have to be overcome.

Owing to the better mixing of the air with the fuel it has been shown to be possible in pulverized-fuel plants to work with very small amounts of excess air, thereby increasing the furnace temperature and reducing the stack loss. Pulverized-fuel plants have of late been able to show a higher efficiency both on this account and because of their well-designed combustion chambers. They also have the advantage of great flexibility, being easy to control, quick steaming, and having no banking loss. If the capital cost of the pulverized-fuel plant can be sufficiently low it will undoubtedly oust the mechanical stoker, but I feel that this is by no means certain.

I think that there is room for very considerable improvement in the design of stoker plant, with corresponding increase in efficiency. Non-compartmented chain grates will of course disappear, and I think that much improved combustion chambers will be evolved. Trouble with the brickwork has caused designers of pulverized-fuel plant to adopt large combustion chambers. Such chambers have made complete combustion of the gases possible before the tubes are reached. The advantage of adequate combustion space is now being appreciated by designers of stoker plant, and I feel sure that a considerable increase in efficiency will result. In the case of very large units the difficulty of providing a stoker with sufficient grate area gives the pulverized-fuel plant a very decided advantage. At present I am keeping an open mind between pulverized-fuel firing and stoker firing in regard to our future extensions.

I have endeavoured to give some outline of what I conceive to be the main possibilities in regard to our future extensions. There is, of course, a mass of practical details to be considered, but I feel that this is not the place to discuss them.

IRON LOSSES IN D.C. MACHINES.*

By EDWARD HUGHES, B.Sc. (Eng.), Associate Member.

(*Paper first received* 11*th March, and in final form* 22*nd April*, 1924.)

SUMMARY.

In Section 1 the iron loss in six d.c. machines with undistorted flux has been analysed to determine :—

(a) The effect of high flux-density upon the hysteresis loss.
(b) The hysteresis and eddy-current exponents over a wide range of flux density.
(c) The ranges of frequency and of flux density over which the total iron loss can be represented by an expression of the form $k_1 f^x B^y$.
(d) The values of k_1, x and y for 0·018 in. lohys laminations.
(e) The agreement between values of iron loss calculated from $k_1 f^{1 \cdot 5} B^2$ with the measured values over wide ranges of frequency and of flux density.

In Section 2 the increase of iron loss with load is examined. The iron loss due to the commutating-pole flux is considered, and a method of calculating the iron loss for any degree of distortion of the main flux is suggested. The values calculated by this method are compared with those measured on a dynamo in which different degrees of distortion were obtained by means of a compensating winding.

SECTION 1. IRON LOSSES WITH UNDISTORTED MAGNETIC FIELD.

A large amount of experimental work has been done on the measurement of rotational hysteresis loss. Practically all investigators except Hermann † have found this loss to be a maximum at a flux density of about 16 000 lines per cm². Hermann employed ring-shaped stampings wound with coils carrying polyphase currents, so that the hysteresis loss measured was due to a mixture of alternating and rotating fluxes. This may account for his failure to detect any difference between rotating and alternating hysteresis losses.

In spite of the fact that all the tests on rotational hysteresis appear to have been carried out on discs resembling a smooth core, many writers have applied the results thus obtained to the calculation of the iron loss in the teeth of armatures, maintaining that at high flux densities the tooth loss does not increase as rapidly as at lower densities, owing to the decrease in the hysteresis loss.

It has been pointed out by Thornton ‡ that as a tooth moves from under a pole shoe "the lines of force become oblique, and midway between the poles horizontal, though the density never drops to zero. There is, therefore, a rotating magnetization in the teeth which is at the same time fluctuating between limits" of 18 000 and 4 000 lines per cm², these values being deduced from his photographs of stream lines. A rough estimation for machine A, the particulars of which are given in Appendix 1, shows that for a flux density of 15 000 in a tooth tip directly under a pole, the tip density due to transverse flux when midway between the poles is reduced to at least 2 500, whilst that at the root of the tooth is reduced to a far greater extent. It therefore follows that the flux in the teeth approaches much more closely to an alternating than to a rotating field; and it was partly for the purpose of checking this conclusion that the experiments dealt with in this paper were undertaken.

The core loss is influenced by so many factors * that it appears almost hopeless to take all of them into account; and judging by the variations in the core loss of even similar machines it seems that the value obtained from a simple expression based upon test-results is almost as reliable as that calculated by the most elaborate formula.

Macfarlane and Burge † give the iron loss in an armature core built of 0·018 in. laminations as

$$W = 7 \cdot 6 \times 10^{-6} f^{1 \cdot 3} (V_a B_a^2 + V_t B_t^2) \text{ watts}$$

where B_a = flux density in armature core in kilolines/cm²,
B_t = average flux density in teeth in kilolines/cm²,
V_a = volume of iron in core in cm³,
V_t = volume of iron in teeth in cm³,
and f = frequency.

A similar result is given by Schukkerman, ‡ namely

$$W = k f^{1 \cdot 3} B^2 V \times 10^{-6} \text{ watts}$$

where k = 7 to 9,
B = mean flux density,
and V = volume of core and teeth in cm³.

Schukkerman found that the index of f increased to 1·45–1·5 at high flux densities, due to the greater ratio of eddy loss to hysteresis loss.

The constants just given apply to ordinary soft-iron laminations. Since most armature cores for d.c. machines are now made with lohys, it seemed desirable to determine whether the above indices apply to this quality of alloyed iron, and also to determine the value of k.

The author was fortunate in having at his disposal

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† A summary of researches on rotational hysteresis loss is given by G. VALLAURI: *Electrician*, 1910, vol. 65, p. 603.

‡ "Distribution of Magnetic Induction and Hysteresis Loss in Armatures," *Journal I.E.E.*, 1906, vol. 37, p. 133.

* A comprehensive discussion on "Iron Losses in D.C. Machines" is given in "Electrical Engineering Papers" by B. G. LAMME, p. 487; see also *Science Abstracts*, 1916, Sec. B, No. 465.

† "Output and Economy Limits of Dynamo-Electric Machinery," *Journal I.E.E.*, 1909, vol. 42, p. 243.

‡ *Science Abstracts*, 1914, Sec. B, No. 1172.

two motor-generator sets fitted with ball bearings, together with a reliable moving-coil ammeter possessing an exceptionally large inertia. It was therefore possible to obtain very accurate and consistent results. The two sets were by the same maker, and one of the machines was fitted with a compensating winding.

Two machines fitted with plain bearings and by different makers were also tested, so as to compare the iron losses with those of the other four machines; but the same accuracy was not possible in these tests.

The losses were in all cases measured by noting the input to a motor directly coupled to the machine under test. The brushes on the latter were lifted to avoid any circulating currents, and a correction was made for

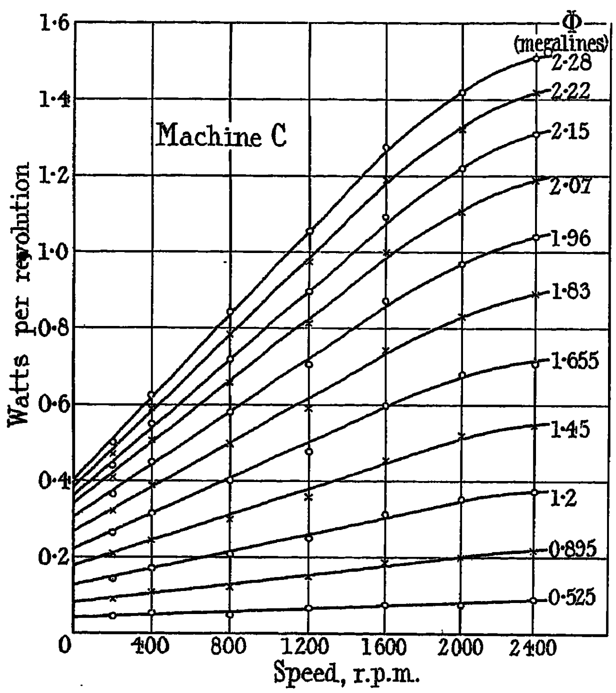

FIG. 1.

the slightly increased copper loss in the motor with increased excitation on the driven machine.

The core dimensions and other particulars of the machines are given in Appendix 1.

The core losses at the various speeds were plotted against flux per pole entering the armature; and from these curves the core loss per revolution was calculated at different fluxes, the curves for machines C and D plotted in Figs. 1 and 2 being typical of the results obtained.

It is of interest to note how W/n deviates from the straight line for speeds of about 1 500 r.p.m. (50 periods per sec.) upwards. This tapering-off of the iron loss was not due to any increase of the armature temperature, since each set of readings took only a few minutes, and several of the tests on these machines were checked by being immediately repeated. The effect in question must therefore be due to the reactance of the eddy-current circuits becoming comparable with their resistance.

From these curves the hysteresis and eddy losses at 1 000 r.p.m. were calculated, the results for machines C and D being plotted in Figs. 3 and 4. It will be noticed that the hysteresis losses for the two machines are approximately the same, but the eddy loss in D is much greater than that in C. This difference is probably due partly if not entirely to the presence of slots in the pole shoes of D, especially as machines A to D are by the same makers and the constants for the iron losses in machines A, B and C are in close agreement (see Table 3). Eddy currents induced in the armature conductors could not be responsible for the

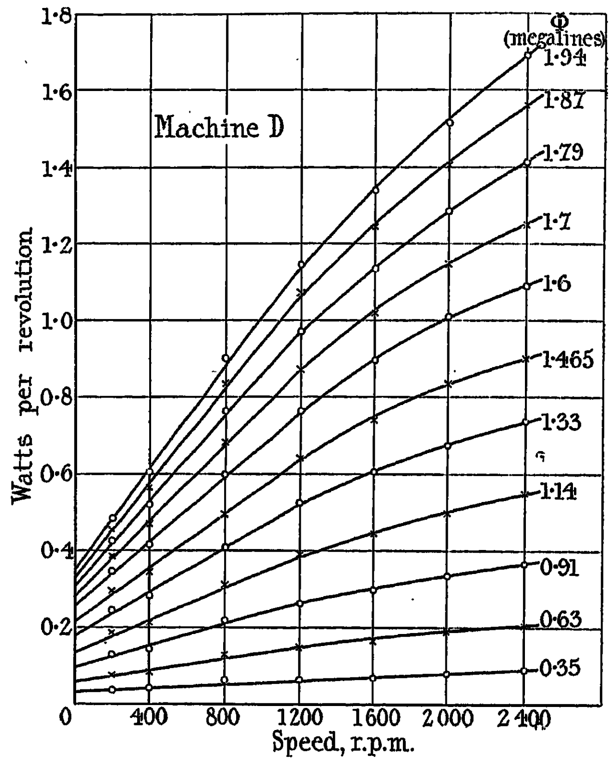

FIG. 2.

increased losses in D; thus, taking the eddy-current loss per cm³ of armature conductor as

$$w = \frac{\pi^2}{6} \cdot \frac{1}{\rho} t_c^2 f^2 B^2_{max.} \times 10^{-16} \text{ watts *}$$

we have for the present case

$$t_c = 0 \cdot 25 \text{ cm}$$

$$f = \frac{1\,000 \times 2}{60} = 33 \cdot 3$$

$B_{max.} = 400$, say, for a flux density of 20 000 in teeth

therefore $w = 0 \cdot 91 \times 10^{-3}$ watts/cm³.

But volume of embedded copper = 643 cm³,

∴ total eddy-current loss in conductors = 0·6 watt.

The curves in Figs. 5, 6 and 7 have been plotted from the logarithms of the flux and of the hysteresis and

* MILES WALKER: "Dynamo-Electric Machinery," p. 144.

eddy-current losses for the six machines. It will be noticed that the slope of most of the curves decreases with decrease of flux density. In each case, however,

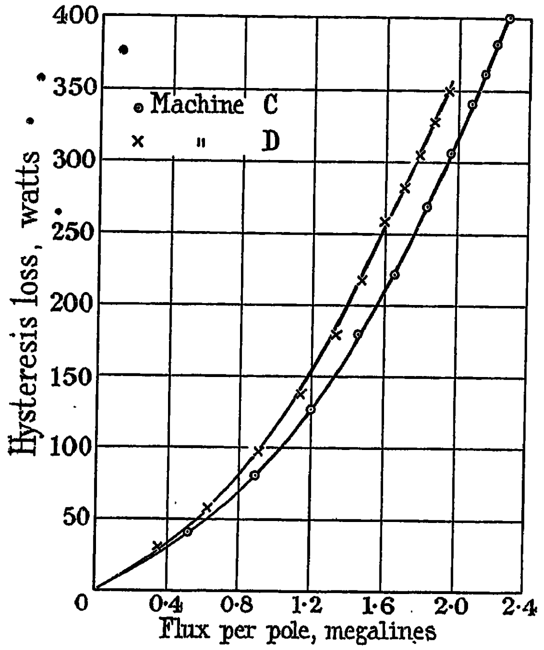

FIG. 3.

a straight line may be drawn through points covering a large range of flux density—including the flux densities usually employed in d.c. machines. To facilitate the

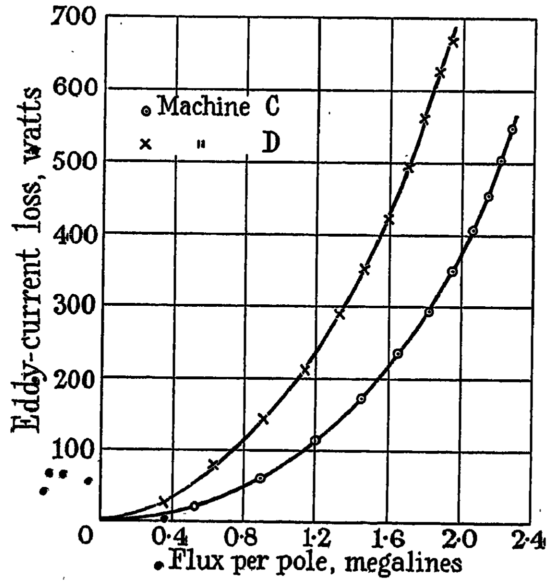

FIG. 4.

comparison of the indices, Table 1 has been compiled from the above curves.

From Table 1 it is seen that the indices for the hysteresis and eddy-current losses vary considerably for different flux densities and for different machines. This illustrates the difficulty of predetermining the iron losses and especially of calculating the losses for the teeth and the core separately.

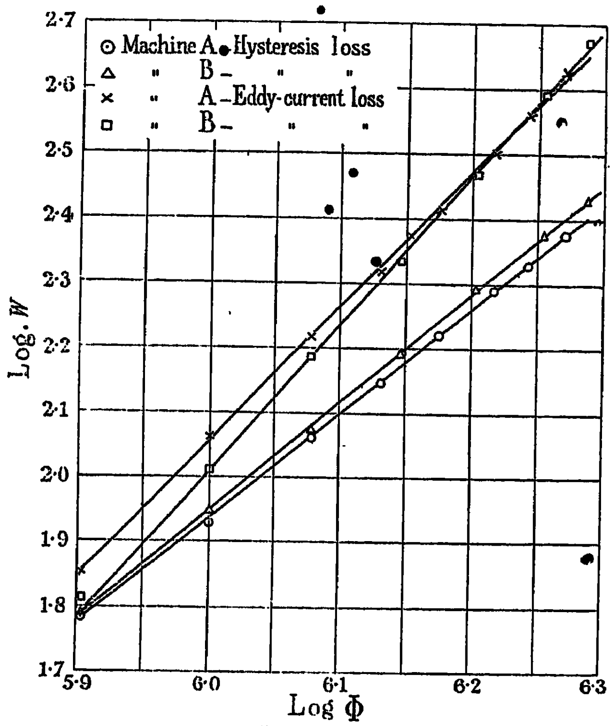

FIG. 5.

It will also be noticed from Figs. 5, 6 and 7 that there is no indication whatever of the hysteresis loss decreasing at high flux densities. Only in the case of machine F —constructed of soft-iron laminations—does the index

TABLE 1.

Machine	Range of apparent flux density in kilolines/cm² at tooth root	Index of Φ	
		Hysteresis loss	Eddy-current loss
A	10–23	1·64	2·08
B	10–23·5	1·68	2·27
C	4·4–10	1·38	2·09
	10–19	1·82	2·44
D	4–10	1·37	1·74
	12·6–21·4	1·72	2·18
E	5·2–13	1·77	2·03
	13–20·7	1·77	2·37
F	6–12	—	2·15
	12–25	—	2·38
	6–18	2·06	—
	18–25	1·52	—

of Φ for the hysteresis loss even decrease. It may therefore be concluded that the results obtained for rotational hysteresis loss in discs at high flux densities are not applicable to toothed armatures. It is of interest to note in connection with Table 1 that Nichol-

TABLE 2.

Machine	Range of speed	Range of apparent flux density at tooth root	Average value of x	Range of speed	Range of apparent flux density at tooth root	Average value of y
	r.p.m.			r.p.m.		
A	350–950	9·8–23	1·487	132–950	12–23	1·85
B	450–950	9·7–23·5	1·567	132–950	12–23·5	1·97
C	750–2 400	7·5–19	1·58	200–2 400	12–19	2·28
D	400–2 400	7–21·4	1·534	200–2 400	12·6–21·4	2·06
E	200–1 700	5·2–20·7	1·32	135–1 760	9–20·7	2·07
F	300–1 400	6–25	1·50	150–1 400	6–22·7	2·14

TABLE 3.

Machine	A_a/A_t	$V_a + (A_a/A_t)^2 V_t$	k_1	k	Thickness and quality of stampings
A	1·566	8 670	0·0252	$2{\cdot}9 \times 10^{-6}$	0·018 in. lohys
B	1·548	8 350	0·0257	$3{\cdot}08 \times 10^{-6}$	0·018 in. lohys
C	1·325	10 050	0·0329	$3{\cdot}27 \times 10^{-6}$	0·018 in. lohys
D	1·72	11 930	0·0501	$4{\cdot}2 \times 10^{-6}$	0·018 in. lohys
E	1·248	3 680	0·0112	$3{\cdot}05 \times 10^{-6}$	0·018 in. lohys
F	2·12	4 690	0·02055	$4{\cdot}38 \times 10^{-6}$	0·018 in. charcoal iron

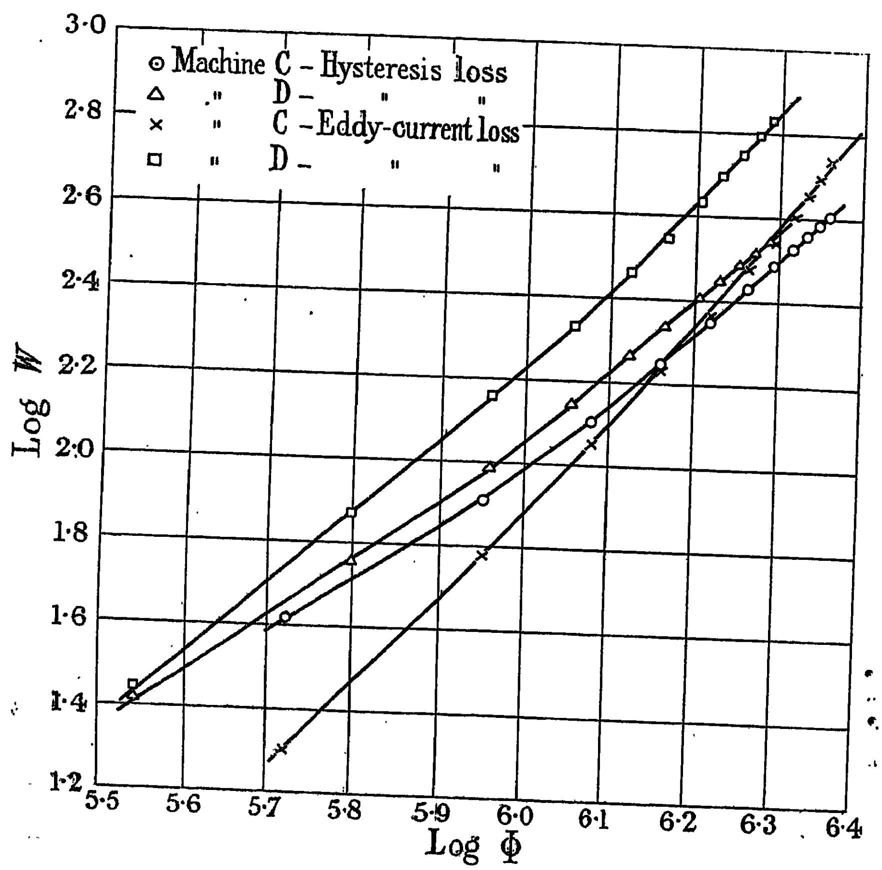

FIG. 6.

son,* working with a sinusoidal flux wave, found that up to a flux density of 19 500 lines/cm^2 the hysteresis loss in stalloy varied as $B_{max.}^{1\cdot 58}$; but that for higher flux densities the index appeared to increase rapidly.

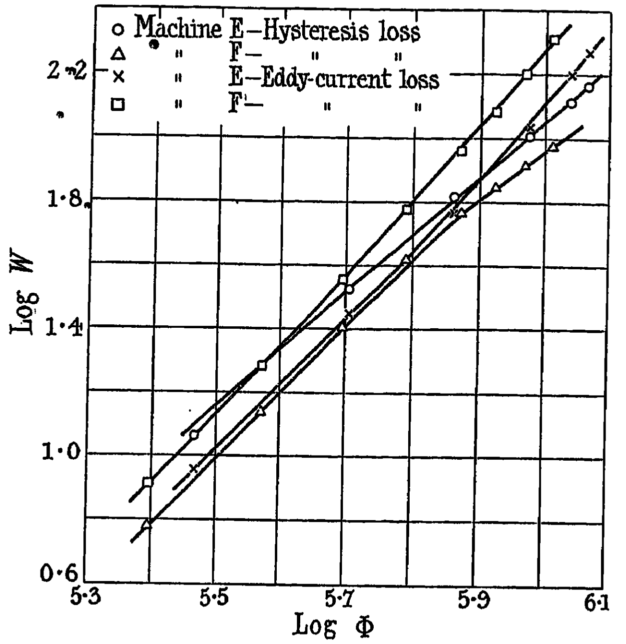

FIG. 7.

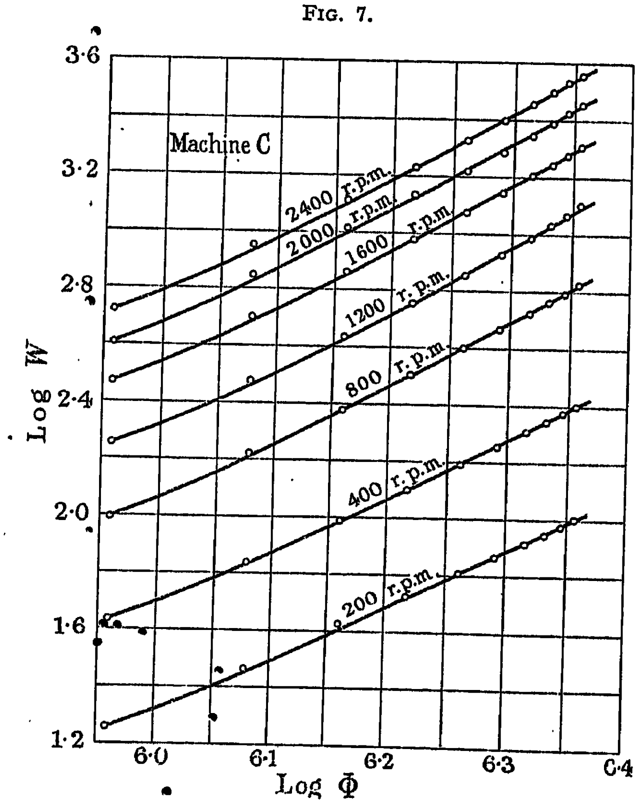

FIG. 8.

* "The Magnetization of Iron at High Flux Density with Alternating Currents," *Journal I.E.E.*, 1915, vol. 53, p. 253.

Also, Lloyd * cites results obtained on a modified Epstein tester, where the hysteresis exponent for the majority of the specimens increased from about 1·6 for a flux density of 5 000 to about 2 for 10 000 lines/cm^2.

In view of the wide variations in the exponents of the hysteresis and eddy-current losses, it was decided to determine the ranges of speed and of flux over which the *total* core loss could be expressed with sufficient accuracy by a simple expression of the form

$$W = an^x\Phi^y$$

where $\qquad n =$ speed in r.p.m.

Curves were drawn of log W against log Φ and also of log W against log n for the various machines at different speeds and at different fluxes respectively. Figs. 8 to 11 for machines C and D are typical of the results obtained; and it will be noticed that the relationships are linear over a large range of flux density and over a surprisingly large range of speed. For purposes of comparison, the results derived from the curves for the six machines are given in Table 2.

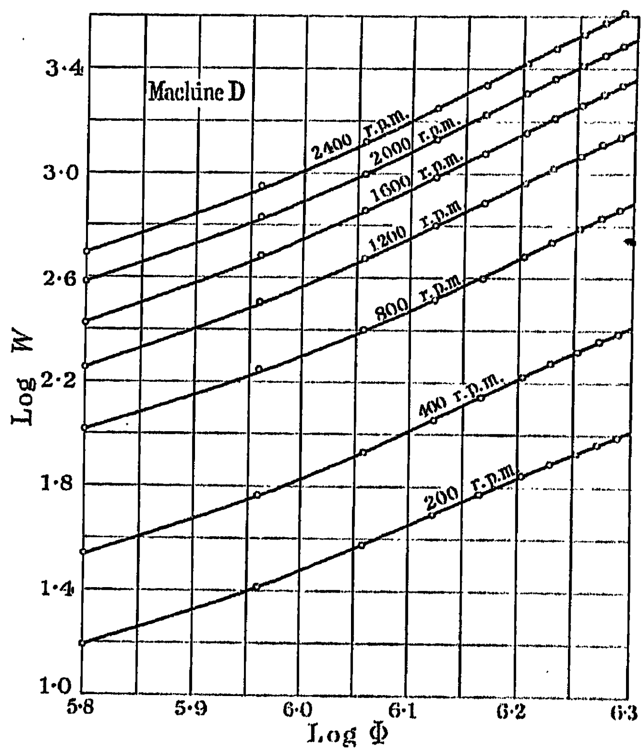

FIG. 9.

The average values of x and y in Table 2 are 1·50 and 2·06 respectively, so that the total iron loss is fairly closely represented by

$$W = an^{1\cdot 5}\Phi^2$$

It will be noticed that the index of the flux is the same as that given by Macfarlane and Burge and by Schukkerman (see page 35), but that the index of the speed or frequency is 1·5 instead of 1·3.

* "Magnetic Testing of Iron," *Electrician*, 1909, vol. 64, p. 319.

A comparison of Tables 1 and 2 and a reference to Figs. 1 and 2 are sufficient to indicate that more consistent values of the exponents for the iron loss are obtained from the total iron loss than from the hysteresis and eddy-current losses considered separately; and that, in general, the values of iron loss calculated from the simple expression $an^{1.5}\Phi^2$ are quite as reliable as those based upon an expression of the form

$$(bn\Phi^{1.7} + cn^2\Phi^2)$$

where b and c are constants for the hysteresis and eddy-current losses respectively.

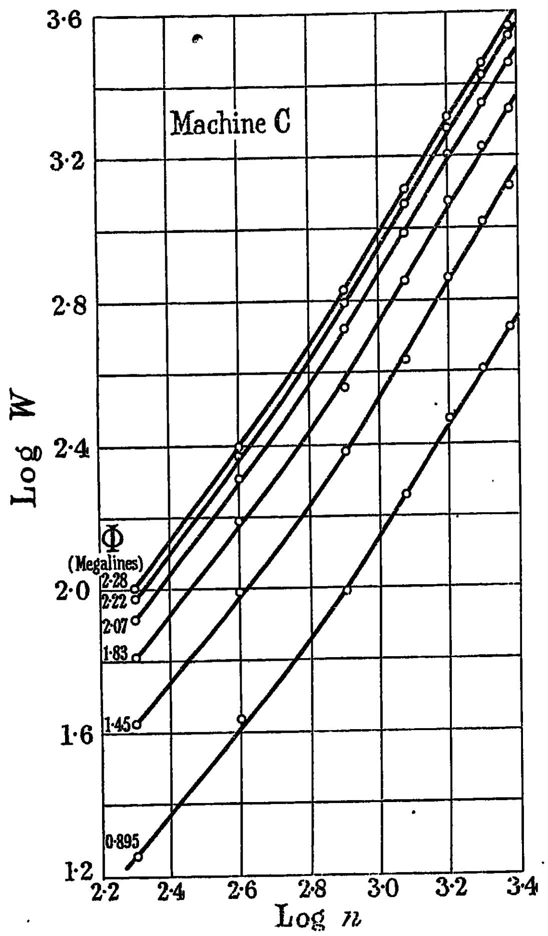

Fig. 10.

Core loss in terms of volume.—Assuming the symbols given on page 35 and making use of the indices just derived, we have:—

$$\text{Total core loss} = W = kf^{1.5}(V_aB_a^2 + V_tB_t^2)$$

If A_a = area of armature core per pole,

and A_t = average area of teeth carrying flux per pole,

then $B_t = \dfrac{A_a}{A_t}B_a$

$$\therefore \quad W = kf^{1.5}B_a^2\{V_a + (A_a/A_t)^2V_t\}$$

$$= k_1f^{1.5}B_a^2 \text{ for a given machine.}$$

The best values of k_1 and of k have been determined for the different machines and are given in Table 3.

The values of k derived for machines A, B, C and E agree very closely with one another, whilst the values for machines D and F are considerably higher. The increased eddy-current loss in D has already been referred to on page 36, and is probably due to the flux pulsation and oscillation caused by the slots containing the compensating winding. The larger coefficient

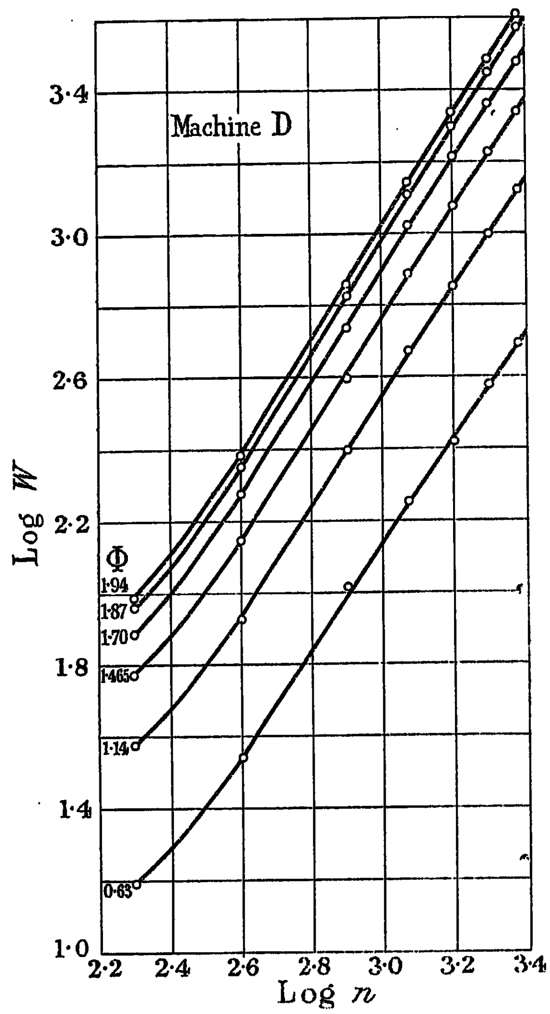

Fig. 11.

for machine F, on the other hand, is mainly due to the laminations being of charcoal iron.

In order to illustrate how closely the core losses calculated from the coefficients given in Table 3 agree with the measured losses, Table 4 has been compiled. For convenience of comparison the ratio of the two values has also been included; and it will be noticed that in the majority of cases the calculated value is within 5 per cent of the measured value over a wide range of frequency and flux density.

Section 2. Influence of Cross Flux and of Commutating-Pole Flux upon Iron Loss in D.C. Machines.

The first section of this paper dealt with undistorted flux, the iron loss being in all cases measured on no

load. When a machine is on load, however, it is well known that the field distortion due to armature reaction increases the iron loss, but it is generally difficult to determine the magnitude of this increase. The weaker the main field in comparison with the cross field, the greater the flux distortion and consequently the greater the increase in the iron loss. There are many cases, such as variable-speed motors, where the predetermination of the iron loss on load is of particular importance, since the maximum load in such machines usually occurs at the highest speed. At the same time, it is necessary to realize that the iron loss depends upon so many factors of construction as well as of material that a very elaborate method of calculating the iron loss is practically useless.

General expressions for eddy-current losses in dynamo teeth and in the pole faces have been derived mathematically by Press * and by Carter †; but these expressions are based upon various assumptions relating to flux distribution, etc., contain unknown constants and are so cumbersome that they are hardly likely to be adopted by the average designer. It is doubtful

TABLE 4.

Machine	Frequency	Core loss		Ratio	Core loss		Ratio	Core loss		Ratio
		Measured	Calculated		Measured	Calculated		Measured	Calculated	
		$B_a = 11·7$			$B_a = 9·38$			$B_a = 6·25$		
A	31·7	594	613	1·032	389	395	1·016	188·5	175·5	0·93
	21·7	345	347·5	1·008	220·5	224	1·015	103·5	99·5	0·962
	15·0	193	200	1·037	126	129	1·022	61	57·2	0·938
	8·3	84	82·5	0·982	55·6	53	0·953	26	23·6	0·908
		$B_a = 12·1$			$B_a = 10·0$			$B_a = 6·25$		
B	31·7	680	672	1·012	451	459	1·018	186	180	0·968
	21·7	363	381	1·05	247	260	1·052	95	101·5	1·068
	15·1	221	221	1·0	150·5	151	1·003	58·5	59	1·008
	8·3	97	90	0·928	67	61·5	0·918	28·5	24·1	0·845
		$B_a = 12·12$			$B_a = 9·73$			$B_a = 6·38$		
C	80·0	3 620	3 460	0·955	2 130	2 230	1·048	895	959	1·071
	53·3	2 040	1 880	0·922	1 190	1 213	1·019	500	521	1·041
	26·7	673	668	0·993	398	429	1·078	166	184·5	1·11
	13·3	250	235	0·939	155	151·5	0·978	69	65	0·942
		$B_a = 10·3$			$B_a = 8·51$			$B_a = 6·06$		
D	80·0	4 060	3 800	0·937	2 615	2 600	0·995	1 315	1 320	1·003
	53·3	2 143	2 070	0·967	1 430	1 415	0·99	710	717	1·01
	26·7	720	732	1·016	478	500	1·045	250	254	1·016
	13·3	242	258	1·066	166	176	1·06	84·5	89·3	1·056
		$B_a = 11·92$			$B_a = 9·67$			$B_a = 5·21$		
E	58·7	729	718	0·985	435	470	1·08	113	136·5	1·21
	36·7	372	354	0·952	230	233	1·012	68	67·8	0·997
	18·3	137	125	0·913	88	82	0·932	26·8	23·8	0·89
		$B_a = 8·42$			$B_a = 6·11$			$B_a = 4·08$		
F	46·7	—	—	—	264	245	0·928	108	109	1·009
	23·3	166	164	0·988	85·8	86·3	1·004	34·7	38·4	1·105
	11·7	57·8	58·4	1·01	31·4	30·7	0·98	13·1	13·65	1·04

* A. PRESS: "Incremental Armature Copper Losses at No-Load and Armature Teeth Eddy-Current Losses," *Journal I.E.E.*, 1915, vol. 53, p. 820.

† F. W. CARTER: "Eddy-Current Losses in Dynamo Teeth," *Electrician*, 1916, vol. 76, p. 569, and "Pole-Face Losses," *Journal I.E.E.*, 1916, vol. 54, p. 168.

whether the results deduced from such expressions, which account for only a portion of the total loss, will be nearer the actual value than those based upon much simpler expressions. In the paper already referred to on page 35, Lamme states that "while the no-load losses are difficult to predetermine, the full-load losses are still much more difficult to calculate," and he then goes on to give a rough qualitative analysis of the problem.

It was with the purpose of discovering whether the incremental iron losses could be calculated easily and fairly accurately over a wide range of speed, load and excitation that the tests described below were carried out. Machine D referred to in Section 1 of this paper was fitted with a compensating winding. By passing a current through the latter and by separately exciting the field winding it was possible to measure the iron losses at different excitations and with different degrees of distortion. The input power was measured as already described on page 36. No current was passed through the C.P.* winding, partly to simplify the test, but mainly because the flux density under the commutating poles due to the current in the compensating winding happened to be approximately what might be expected in a normal machine. The brushes were lifted off the commutator to eliminate any currents circulating round the armature winding. Fig. 12 shows the results obtained at 2 000 r.p.m., these curves being typical of those obtained at the other speeds; and the losses at different speeds, etc., are given in Table 5.

The iron losses in the machine under test may be resolved into :—

(*a*) Iron loss in teeth under commutating poles.
(*b*) Iron loss in teeth under main poles.
(*c*) Iron loss in armature core.

(*a*) *Iron loss in teeth under commutating poles.*—It is curious that this loss is never referred to as being partly responsible for the incremental loss. This is probably due to the impression that owing to the comparatively low flux density and the short duration of the period of magnetization the iron loss is negligibly small. This, however, is far from being the case. For instance, the hysteresis loss per period depends upon the maximum flux density and is independent † of frequencies obtaining in a d.c. machine. The period of magnetization is slightly unsymmetrical, but the effect is too small to be detected (see page 50). It therefore matters not whether a tooth be passing a commutating pole or a main pole; the hysteresis loss per cm³ per period is exactly the same for a given maximum flux density. From this point of view the integration method suggested by Thornton ‡ for calculating the heating effect of hysteresis loss in an armature is not correct.

Let us next consider the eddy-current loss. This loss may be regarded as being due to two distinct causes; first, the teeth in moving through the flux generate an E.M.F. in just the same way as do the

* Commutating pole.
† M. G. Lloyd: "Magnetic Testing of Iron," *Electrician*, 1909, vol. 64, p. 319; and M. Rosenbaum: "Hysteresis Loss in Iron taken through Unsymmetrical Cycles of Constant Amplitude" *Journal I.E.E.*, 1912, vol. 48, p. 534.
‡ W. M. Thornton: "The Distribution of Magnetic Induction and Hysteresis Loss in Armatures," *Journal I.E.E.*, 1906, vol. 37, p. 125.

TABLE 5.

Field current	0 ampere				0·31 ampere					0·6 ampere				
*Current in Comp. Winding	Amperes				Amperes					Amperes				
Speed, r.p.m.	50	100	150	200	0	50	100	150	200	0	50	100	150	200
200	11	26	43	63	11·3	19·7	32·7	47·8	68·4	26	32	42·5	55·5	71·7
400	20	54	93	152·5	25·5	41	68	106·5	161	58	70	91·5	125·5	175·5
800	65	170	302	465	75	123	211	324	476	175	217	277	375	512
1 200	113	274	520	853	124	221	377	600	908	317	400	518	714	980
1 600	138	480	825	1 285	185	332	595	918	1 367	477	590	780	1 075	1 430
2 000	255	600	1 100	1 810	270	485	780	1 220	1 850	680	855	1 080	1 450	1 975
2 400	310	830	1 465	2 290	350	635	1 095	1 700	2 475	830	1 130	1 460	2 010	2 730

Field current	1·4 amperes					2·2 amperes				
*Current in Comp. Winding	Amperes					Amperes				
Speed, r.p.m.	0	50	100	150	200	0	50	100	150	200
200	69·2	74	80·3	88·4	98·5	97·3	100·7	105·1	111·2	120·8
400	166	177	192	215	243·5	242	248	257·5	274	304·5
800	478	513	558	624	709	720	740	773	826	898
1 200	918	967	1 045	1 165	1 322	1 373	1 404	1 455	1 565	1 719
1 600	1 430	1 490	1 605	1 745	2 010	2 143	2 190	2 255	2 345	2 530
2 000	2 020	2 120	2 245	2 500	2 850	3 030	3 075	3 160	3 340	3 570
2 400	2 615	2 765	2 985	3 350	3 770	4 060	4 190	4 300	4 620	5 014

armature conductors. The path of the eddy currents due to these "speed" E.M.F.'s is mainly radial, but it seems impossible to calculate the resistance of this path with any degree of accuracy. The main features of these eddies, however, is that they are directly proportional to the flux density and that their duration is practically proportional to the width of the C.P. shoe. Consequently the loss due to these eddies should be comparatively small.

The second cause of eddy-current loss is the transformer action that occurs in each tooth as it moves into and out of a magnetic field, eddy currents being induced transversely in the tooth of each lamination. So long as a tooth is moving in a field of uniform strength, the loss due to this cause is zero. Consequently, the width of the pole arc has no effect, and the loss for a given flux density is just as large when a tooth passes into and out of the C.P. field as when it passes into and out of the main-pole field.

Circumstances prevented the author from carrying out any further tests on machine D, so that it was not possible to check the iron loss due to the C.P. flux alone for that machine. Tests were therefore carried out on another machine G of about the same size, and in order to avoid confusion at this point the results are given in Appendix 2. The conclusions from these tests, however, may be briefly stated thus:—

(i) The polarity of the commutating poles relatively to that of the main poles has no measurable effect upon the loss due to C.P. flux.

(ii) The increase in the iron loss due to a given current in the C.P. winding is practically independent of the flux in the main poles.

(iii) The loss due to the C.P. flux calculated from the expression $kf^{1.5}B^2V_t$ with the value of k derived from the loss due to the main-pole flux alone, agrees fairly closely with the actual loss over a wide range of C.P. flux.

These results enable us to proceed with the calculation of the loss in the teeth under the commutating poles, the figures for machine D being:—

Length of C.P. gap = $0\cdot254$ cm
Tooth pitch at tip = $2\cdot8$ cm
Width of slot = $1\cdot15$ cm

Carter's correction coefficient = $0\cdot485$ for present case.

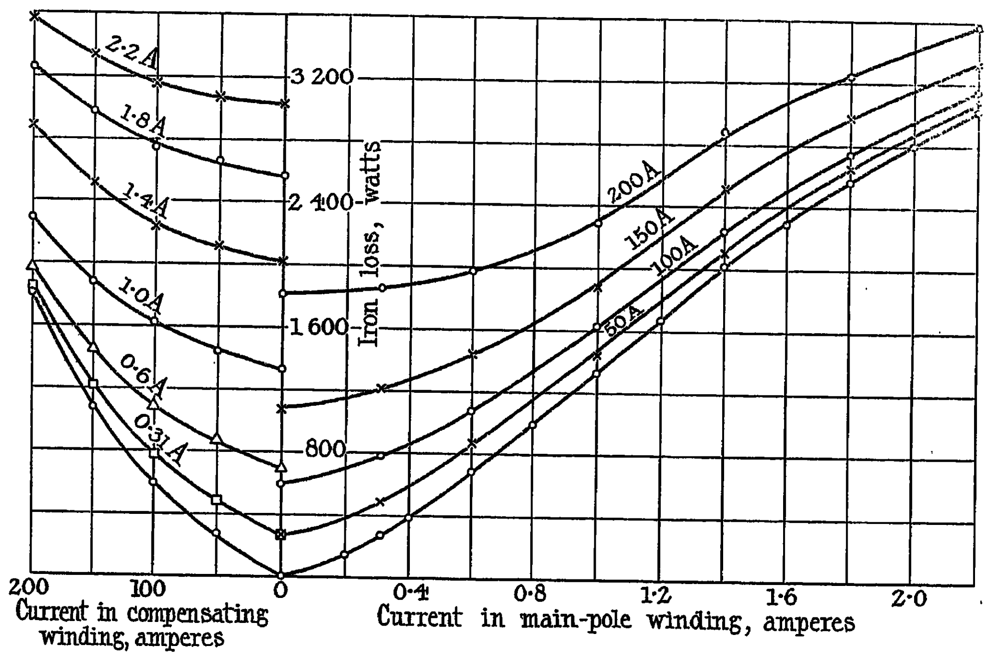

FIG. 12.

∴ Effective length of C.P. gap

$$= 0\cdot254 \times \frac{2\cdot8}{2\cdot8 - 0\cdot485 \times 1\cdot15}$$
$$= 0\cdot317 \text{ cm.}$$

With 200 amperes in the compensating winding the ampere-turns per pole acting on the C.P. magnetic circuit is

$$200 \times 6 = 1\,200$$

If the reluctance of the iron portion of the magnetic circuit be neglected in comparison with that of the air-gap, then the average flux density in C.P. air-gap

$$= \frac{1\,200}{0\cdot8 \times 0\cdot317}$$
$$= 4\cdot74 \text{ kilolines/cm}^2.$$

Size of C.P. shoe = $11 \cdot 44 \times 3 \cdot 175$ cm.
Flux per tooth pitch per cm axial length of core

$$= 4 \cdot 74 \times 2 \cdot 8$$
$$= 6 \cdot 91 \text{ kilolines.}$$

Average wide of tooth = $1 \cdot 41$ cm.

$$\therefore \text{Average flux density in tooth} = \frac{6 \cdot 91}{1 \cdot 41 \times 0 \cdot 9}$$
$$= 5 \cdot 45 \text{ kilolines/cm}^2.$$

The armature core had two vent ducts under the C.P. shoe, so that the effective length of core carrying flux under the commutating poles may be taken to be approximately the same as that of the C.P. shoe.

Hence volume of teeth subjected to the C.P. flux is

$$1 \cdot 41 \times 2 \cdot 86 \times 11 \cdot 44 \times 0 \cdot 9 \times 37 = 1\,530 \text{ cm}^3.$$

In Section 1 it was found that the iron loss of this machine is given by

$$W = 4 \cdot 2 \times 10^{-6} f^{1 \cdot 5} B^2 V$$

Hence, at 2 000 r.p.m. and with 200 amperes in the compensating winding, iron loss in teeth under C.P.

$$= 4 \cdot 2 \times 10^{-6} \times \left(\frac{2\,000 \times 2}{60}\right)^{1 \cdot 5} \times (5 \cdot 45)^2 \times 1\,530$$
$$= 383 \text{ watts.}$$

The effect upon the C.P. flux of its superposition upon the main-pole flux in certain portions of the yoke was estimated, but the reduction was found to be comparatively small; and any effect upon the loss is negligible, as shown experimentally in Appendix 2.

If the C.P. flux be assumed proportional to the current in the compensating winding, then iron loss in teeth under C.P. is 215 watts with 150 amperes, 96 watts with 100 amperes and 24 watts with 50 amperes.

(*b*) *Iron loss in teeth under main poles.*—The remarks concerning hysteresis and eddy-current losses made in connection with the C.P. flux apply equally well here. The problem is further complicated, however, by the fact that the flux density varies over the pole face and may even become reversed, as indicated in Fig. 14, when the main field is weak relatively to the cross field.

If the magnetization curve be as represented in Fig. 15, then for an excitation OA with undistorted field, the flux density is uniform and proportional to AH.

Let I = total current through armature,
q = number of parallel circuits through armature,
C = total number of armature conductors,
p = pairs of poles,
and ψ = pole arc/pole pitch.

Then cross ampere-turns per pole acting at pole-tips

$$= \frac{I}{q} \cdot \frac{C}{2} \cdot \frac{\psi}{2p}$$

If AC and AB be made to represent these cross ampere-turns per pole, the distribution of the flux over the pole arc is given fairly closely by the curve JHG. Further refinements in determining this distribution are hardly justifiable in the present problem. The flux per pole is therefore given by BN, the average height of JHG; and the maximum density at the mean section of the teeth is given by

$$B_1 = \frac{\text{flux CG}}{\text{average area of teeth carrying flux per pole}}$$
$$= \frac{\text{flux CG}}{109 \cdot 25} \text{ for the present case.}$$

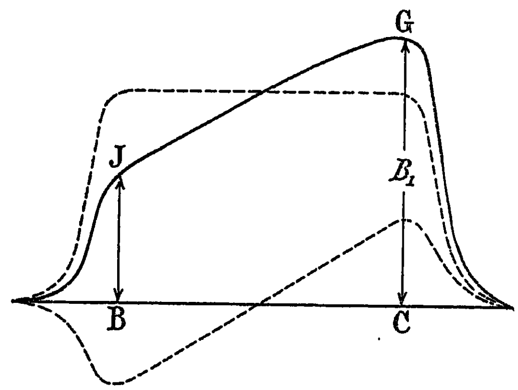

FIG. 13.

With a comparatively weak excitation, such as OD, the flux distribution is represented by Fig. 14, the resultant flux per pole being given by the average height FP of the curve MLK. The flux density at

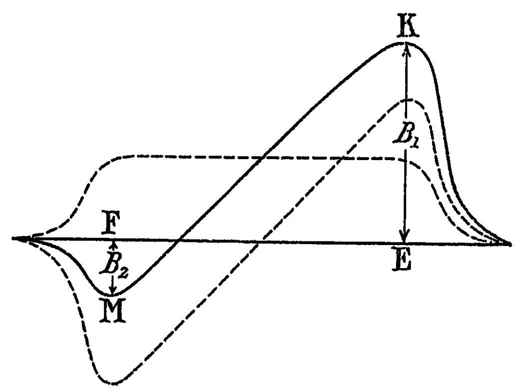

FIG. 14.

the mean section of the teeth under one pole-tip is given by $B_1 = \dfrac{\text{flux EK}}{109 \cdot 25}$, whilst that under the other pole-tip is given by $B_2 = \dfrac{\text{flux FM}}{109 \cdot 25}$.

The hysteresis loss in the teeth with a flux distribution as in Fig. 13 depends only upon the flux density corresponding to CG; but with a flux distribution like that of Fig. 14 the hysteresis loss is made up of two distinct components, namely that due to magnetization EK and that due to magnetization FM.

The effect of distortion upon the eddy-current loss may be considered in a general way thus :—

Suppose the distribution of undistorted flux round the periphery of the armature to be represented by

$$B_\theta = B_1 \sin\theta \pm B_3 \sin 3\theta \pm B_5 \sin 5\theta \pm \quad . \quad . \quad .$$

where B_1, B_3, etc., are the amplitudes of the fundamental and harmonic flux waves.

Then E.M.F. generated by rotation in flux density B_θ $\Big\} \propto B_\theta$

$\therefore$ corresponding value of eddy loss per cm³ $\Big\} \propto B_\theta^2$

$$= kB_\theta^2$$

where k is a constant.

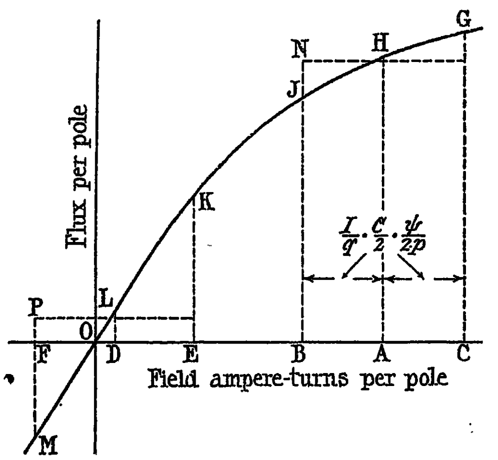

FIG. 15.

Hence average value of eddy loss per cm³ over pole pitch

$$= \frac{k}{\pi}\int_0^\pi B_\theta^2 d\theta$$

$$= \frac{k}{2}(B_1^2 + B_3^2 + B_5^2 + \ldots) \quad . \quad . \quad . \quad (1)$$

Again, instantaneous E.M.F. induced in teeth by transformer action

$$\propto \frac{d}{d\theta}B_\theta$$

$$\propto (B_1 \cos\theta \pm 3B_3 \cos 3\theta \pm 5B_5 \cos 5\theta \pm \ldots)$$

$\therefore$ corresponding value of eddy loss per cm³

$$= k_1(B_1 \cos\theta \pm 3B_3 \cos 3\theta \pm 5B_5 \cos 5\theta \pm \ldots)^2$$

where k_1 is another constant.

Hence average value of eddy loss per cm³ over pole pitch

$$= \frac{k_1}{\pi}\int_0^\pi (B_1 \cos\theta \pm 3B_3 \cos 3\theta \pm 5B_5 \cos 5\theta \pm \ldots)^2 d\theta$$

$$= \frac{k_1}{2}(B_1^2 + 9B_3^2 + 25B_5^2 + \ldots) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

A comparison of expressions (1) and (2) shows that harmonics in the flux wave have a much greater effect upon the eddy loss due to transformer action than upon that due to rotation.

Let us next consider the effect of distortion. If saturation were neglected, the distribution of the cross flux would be symmetrical and could be represented by an expression of the form

$$B_{c\theta} = B_{c1} \sin(\theta - 90) \pm B_{c3} \sin 3(\theta - 90) \pm B_{c5} \sin 5(\theta - 90) \pm \ldots$$
$$= B_{c1} \sin(\theta - 90) \pm B_{c3} \sin(3\theta + 90) \pm B_{c5} \sin(5\theta - 90) \pm \ldots$$

Hence the fundamental and the harmonics of the cross-flux wave are each in quadrature with the fundamental and respective harmonics of the main-flux wave.

$\therefore$ amplitude of resultant fundamental $= \sqrt{(B_1^2 + B_{c1}^2)}$

amplitude of resultant 3rd harmonic $= \sqrt{(B_3^2 + B_{c3}^2)}$

etc.

It can therefore be shown that the average value of eddy loss per cm³ due to rotation

$$= \tfrac{1}{2}k(B_1^2 + B_{c1}^2 + B_3^2 + B_{c3}^2 + \ldots)$$

and average value of eddy loss per cm³ due to transformer action

$$= \tfrac{1}{2}k_1\{B_1^2 + B_{c1}^2 + 9(B_3^2 + B_{c3}^2) + 25(B_5^2 + B_{c5}^2) + \ldots\}$$

It will be obvious from Figs. 13 and 14 that the wave of cross flux consists mainly of harmonics, so that a relatively large increase of eddy-current loss must result. But the amplitudes of these harmonics vary with every variation of the main-pole excitation, and the relation between the eddy loss due to transformer action and that due to rotation is not known and could only be calculated very crudely; consequently it would not be worth while to analyse the flux waves for any particular case. The principal deduction from the above analysis, however, is that the iron loss in the teeth increases rapidly with flux distortion, and may therefore be regarded as being dependent upon the maximum flux density; but the extent of this dependence can only be checked by experiment.

The flux distribution under the main pole of machine D was determined from the magnetization curve for each of the various field excitations and currents in the compensating winding. The flux density at the mid-section of a tooth was calculated under the strengthened pole-tip; and in those cases where the field under the other pole-tip was reversed, the corresponding flux density was also calculated.

If B_1 = flux density in kilolines/cm² at the mid-point of a tooth under the strengthened pole-tip,

B_2 = corresponding value for a tooth under the other pole-tip, when the flux is reversed as in Fig. 14,

and V_t = total volume of teeth in cm³,

then the iron loss in the teeth has been calculated from

$$W_t = 4{\cdot}2 \times 10^{-6} f^{1{\cdot}5} V_t (B_1^2 + B_2^2) \text{ watts.}$$

At a speed of 2 000 r.p.m.,

$$W_t = 4{\cdot}2 \times 10^{-6} \times \left(\frac{2\,000 \times 2}{60}\right)^{1{\cdot}5} \times 1\,880(B_1^2 + B_2^2)$$
$$= 4{\cdot}31(B_1^2 + B_2^2).$$

(c) *Iron loss in armature core.*—It has already been pointed out (page 43) that the C.P. flux appears to have no effect upon the loss due to the main flux. This is probably due partly to the main-pole flux causing a slight decrease of the C.P. flux and reducing the iron loss in the teeth under the commutating poles by about the same amount as any increase of the core loss; and partly to the C.P. flux altering the distribution of flux in the armature core rather than increasing the density in those parts where the density due to the main flux is already high.

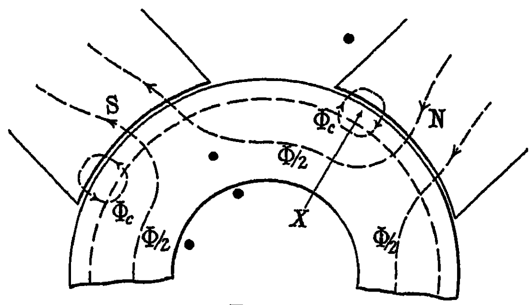

Fig. 16.

When the distribution is of the form indicated in Fig. 13, the flux density in the armature core is obtained from the total flux per pole represented by BN in Fig. 15. With such a distribution as that of Fig. 14, on the other hand, the flux which re-enters the pole-face has to be carried by a part of the armature core that is working at a comparatively high flux density, the distribution of flux over the cross-section being far from uniform.* Hence if Φ be the resultant flux per pole, Φ_c the cross-flux re-entering the pole-shoe, and A the sectional area per pole of the armature core, then average flux density at section X (Fig. 16)

$$= B_a = (\tfrac{1}{2}\Phi + \Phi_c) \div \tfrac{1}{2}A$$
$$= \frac{\Phi + 2\Phi_c}{A}$$

The value of Φ_c can be derived from Fig. 15 thus:—

Φ_c = average ordinate of curve OM(OF/FE)
$\doteqdot \tfrac{1}{2}$FM(OF/FE)

The value of Φ is given by FP, the average ordinate of curve MLK, as already explained on page 44.

Table 6.

Field current	Current in compensating winding	Flux Φ	Flux Φ_c	Loss in teeth under C.P.	Loss in teeth under main poles	Loss in armature core	Total calculated loss	Measured loss
amps.	amps.	megalines	megalines	watts	watts	watts	watts	watts
0·31	0	0·5	0	0	90·5	103·5	194	270
0·6		0·91	0	0	298	343	641	680
1·4		1·6	0	0	920	1 060	1 980	2 020
2·2		1·94	0	0	1 360	1 555	2 915	3 030
0	50	0	0·1251	24	61+61	26	172	255
0·31		0·4925	0	24	267	100	391	485
0·6		0·8964	0	24	520	332	876	855
1·4		1·594	0	24	1 075	1 050	2 149	2 120
2·2		1·9375	0	24	1 470	1 550	3 044	3 075
0	100	0	0·2418	96	224+224	96	640	600
0·31		0·46	0·06	96	484+37	139	756	780
0·6		0·85	0	96	718	298	1 112	1 080
1·4		1·568	0	96	1 220	1 010	2 326	2 245
2·2		1·9265	0	96	1 560	1 530	3 186	3 160
0	150	0	0·3413	215	428+428	192	1 263	1 100
0·31		0·4193	0·1607	215	688+182	227	1 312	1 220
0·6		0·7825	0·0433	215	888+ 25	312	1 440	1 450
1·4		1·528	0	215	1 335	962	2 512	2 500
2·2		1·914	0	215	1 660	1 515	3 390	3 340
0	200	0	0·426	383	648+648	300	1 979	1 810
0·31		0·3725	0·2567	383	868+383	323	1 957	1 850
0·6		0·7193	0·126	383	1 050+157	391	1 981	1 975
1·4		1·4675	0	383	1 460	890	2 733	2 850
2·2		1·89	0	383	1 745	1 475	3 603	3 570

* W. M. Thornton: "The Distribution of Magnetic Induction and Hysteresis Loss in Armatures," *Journal I.E.E.*, 1906, vol. 37, p. 125.

If B_a = flux density in kilolines/cm², and V_a = volume of armature core in cm³, then iron loss in armature core

$$= W_a = 4\cdot 2 \times 10^{-6} f^{1.5} B_a^2 V_a$$

At a speed of 2 000 r.p.m.,

$$W_a = 4\cdot 2 \times 10^{-6} \times \left(\frac{2\,000 \times 2}{60}\right)^{1\cdot 5} \times 6\,370 B_a^2$$

$$= 14\cdot 6 B_a^2$$

Comparison of calculated losses with measured losses.—The losses have been calculated for a speed of 2 000 r.p.m. and the results are incorporated in Table 6; and in order to show how the calculated values and the measured values compare over a wide range of speed, excitation and distortion, Table 7 has also been compiled. It will be seen that the figures agree remarkably well, considering the simple expressions employed and the very wide ranges covered. The agreement is as good as is required in the calculation of iron losses unless the conditions are exceptional.

It may be added that 200 amperes through the compensating winding of the machine under test corresponds to an armature loading of 214 ampere-conductors per cm of the periphery.

TABLE 7.

Field current	0 ampere				0·6 ampere				2·2 amperes			
Current in Comp. winding	Amperes				Amperes				Amperes			
	100		200		100		200		100		200	
Speed	C*	M†	C	M	C	M	C	M	C	M	C	M
r.p.m.												
200	20·2	26	62·5	63	35·2	42·5	62·6	71·7	101	105·1	114	120·8
400	57·1	54	176·5	152·5	99	91·5	177	175·5	284	257·5	322	304·5
800	162	170	500	465	281	277	502	512	805	773	910	898
1 200	297	274	917	853	516	518	920	980	1 480	1 455	1 675	1 719
1 600	458	480	1 412	1 285	795	780	1 420	1 480	2 280	2 255	2 580	2 530
2 000	640	600	1 979	1 810	1 112	1 080	1 981	1 975	3 186	3 160	3 603	3 570
2 400	841	830	2 600	2 290	1 465	1 460	2 610	2 730	4 190	4 300	4 750	5 014

* Denotes "calculated." † Denotes "measured."

CONCLUSIONS.

Section 1.

(1) In a d.c. machine the hysteresis loss varies as B^x, where x lies between about 1·6 and 1·8, and the eddy-current loss varies as B^y, where y lies between about 2 and 2·4.

(2) The hysteresis loss in a toothed armature does not show any sign of decreasing with increasing flux densities of the values generally employed in d.c. armatures. Up to an apparent flux density of 23·5 kilolines/cm² at the tooth root, the hysteresis exponent remains constant over a large range of flux density; hence results obtained for rotational hysteresis loss are not applicable to armature teeth.

(3) The eddy-current exponent is generally greater than 2, even for comparatively low flux densities. This appears to be mainly due to the flux distribution in the armature core becoming less uniform with increasing excitation.

(4) Above about 50 periods per second, the eddy-current loss does not continue to increase as the square of the frequency.

(5) More consistent values of the exponents of B and f are obtained from the total iron loss than from the hysteresis and eddy-current losses separately; and the total iron loss can be calculated with fair accuracy over wide ranges of frequency and of flux density from the expression

$$W = kf^{1\cdot 5}(V_a B_a^2 + V_t B_t^2)$$

$$= k_1 f^{1\cdot 5} B_a^2 \text{ for a given armature,}$$

where B_a = flux density in armature core,

and B_t = mean flux density in teeth.

(6) The value of k for lohys laminations, 0·018 in. thick, may be taken as 3×10^{-6} when the flux density is in kilolines/cm² and the volume in cm³.

In terms of the weight in lb. of the armature core and teeth, the iron loss may be expressed as

$$W = k_2 f^{1\cdot 5}(W_a B_a^2 + W_t B_t^2)$$

where $k_2 = 58\cdot 2k$
$= 1\cdot 75 \times 10^{-4}$ for 0·018 in. lohys.

Thus for a flux density of 10 kilolines/cm² at 50 periods per second,

$$\text{Iron loss per lb.} = 1\cdot75 \times 10^{-4} \times (50)^{1\cdot5} \times (10)^2 = 6\cdot18 \text{ watts.}$$

It is of interest to note that the makers give the loss as 1·55 watts per lb. when the laminations are tested with an alternating flux under the most favourable conditions. It may also be pointed out that the value of the core loss to be found in most textbooks on dynamo design are much smaller than those given in this paper.

For convenience in the application of the above formulæ, the iron loss at different frequencies and flux densities has been plotted in Fig. 17.

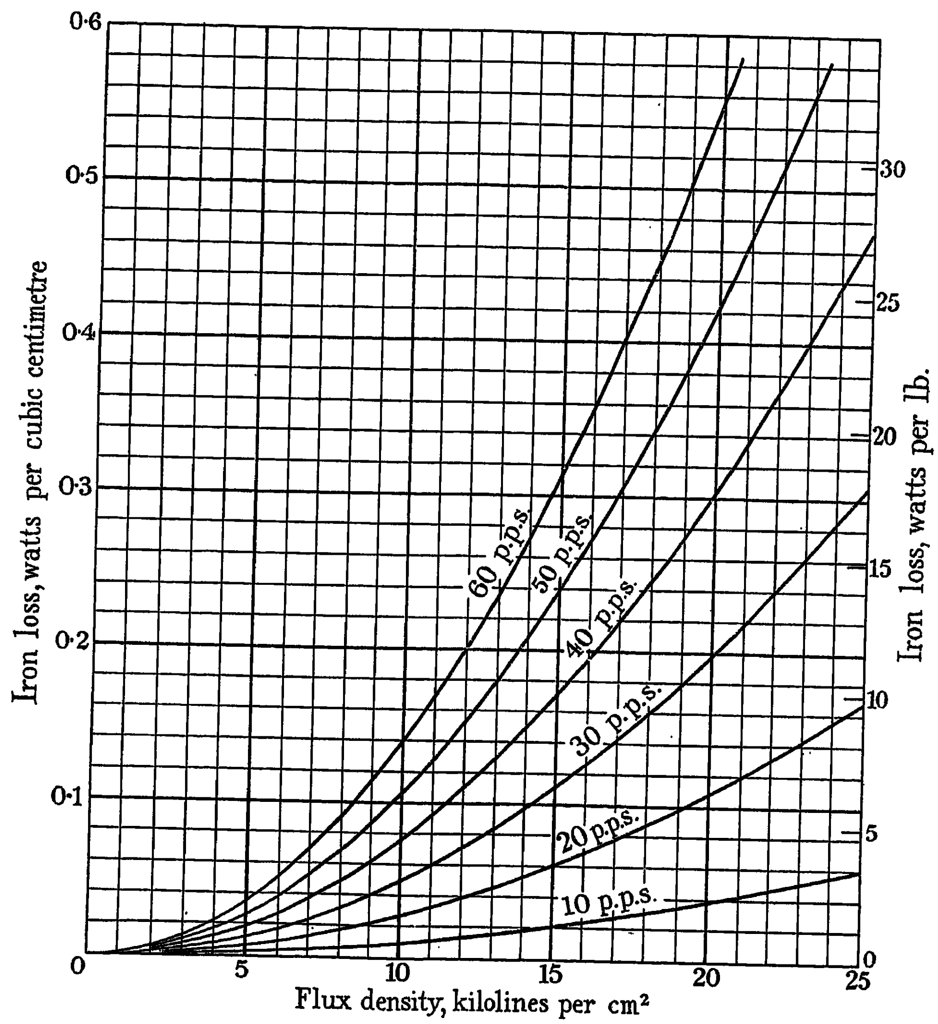

FIG. 17 —Iron loss in 0·018 in. lohys laminations for d.c. machines.

Section 2.

(1) The increase of iron loss due to a given current in the C.P. winding is independent of the flux in the main poles.

(2) The polarity of the commutating poles relatively to that of the main poles has no effect upon the loss due to the C.P. flux.

(3) The total iron loss with any degree of distortion is given fairly closely by the sum of the following losses :

(*a*) Tooth loss due to C.P. flux $= W_c = kf^{1\cdot5}B_t^2V_t'$

where k = constant derived for iron loss with undistorted field,
f = frequency of machine,
B_t = mean flux density in teeth under C.P.,
and V_t' = volume of teeth subjected to C.P. flux.

(*b*) When flux is not reversed at one pole-tip, tooth loss due to main-pole flux is

$$W_t = kf^{1\cdot5}B_1^2V_t$$

When flux is reversed at one pole-tip (Fig. 14), tooth loss due to main-pole flux is

$$W_t = kf^{1\cdot5}(B_1^2 + B_2^2)V_t,$$

where k = same constant as before,
V_t = total volume of teeth,
B_1 = mean flux density in tooth under strengthened pole-tip,

$$= \frac{\text{flux KE}}{\text{mean area of teeth carrying flux per pole for excitation OD (Fig. 15)}},$$

and B_2 = ditto under pole-tip at which flux is reversed

$$= \frac{\text{flux FM}}{\text{mean area of teeth carrying flux per pole for excitation OD.}}$$

(c) Loss in armature core $= W_a = kf^{1\cdot5}B_a^2 V_a$

where k = same constant as above,
V_a = volume of armature core carrying flux,
and

$$B_a = \frac{\Phi + 2\Phi_c}{A}$$

where Φ = resultant flux per pole,
Φ_c = cross flux (if any) re-entering pole-shoe, $\fallingdotseq \frac{1}{2}$FM(OF/FE) in Fig. 15,
and A = sectional area per pole of magnetic circuit through armature core.

Then total iron loss $= W_c + W_t + W_a$.

The author wishes to thank Prof. F. G. Baily for permission to carry out the tests on machines A to D at the Heriot-Watt College, Edinburgh. The remainder of the work was done at the Municipal Technical College, Brighton.

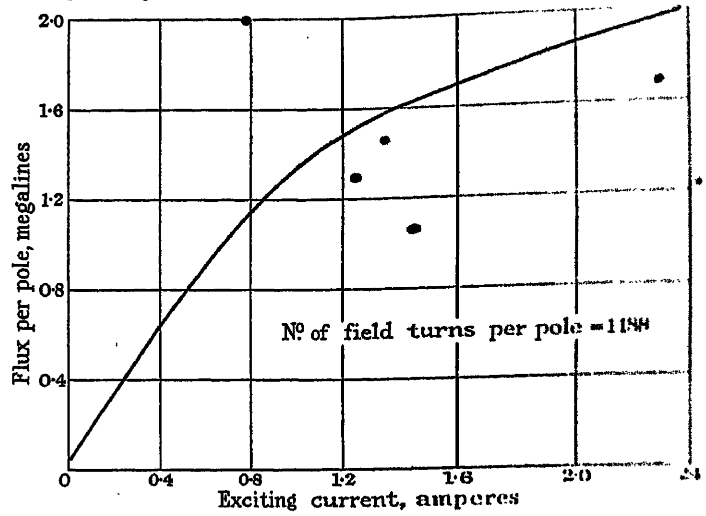

Fig. 18.

APPENDIX 1.

Note.—Particulars of the machines referred to in the paper.

Machine	A	B	C	D	E	F	G
No. of poles	4	4	4	4	4	4	4
Diam. of armature, cm ..	30·52	30·34	33	33	21·6	19·05	33
Gross length of armature, cm	15·23	15·23	16·5	16·5	15·22	12·7	25·4
No. and size of vent ducts ..	(2) ½ in.	(2) ½ in.	(2) ½ in.	(2) ½ in.	(1) ⅜ in.	None	(2) ⅜ in.
No. of slots	49	49	41	37	25	29	39
Size of slot, cm	3·02×0·813	2·84×0·813	2·86×0·838	2·86×1·15	2·86×1·08	2·285×0·95	3·3×1·17
Pole arc/Pole pitch	0·75	0·75	0·75	0·645	0·737	0·768	0·69
Mean area of teeth carrying flux per pole, cm²	102·2	103·4	142	109·2	78·5	57·3	179·2
Area of armature core per pole, cm²	160	160	188	188	97·8	121·8	290
Volume of teeth, cm³ ..	1 605	1 510	2 100	1 880	1 172	654	3 340
Volume of armature core carrying flux, cm³	4 740	4 740	6 370	6 370	1 860	1 750	8 920
No. of armature conductors ..	—	—	—	444	—	—	488
Type of winding	—	—	—	Lap	—	—	Wave
No. of turns per pole on compensating winding	—	—	—	6	—	—	—

The magnetization curve for Machine D is given in Fig. 18.

APPENDIX 2.

The tests described below were carried out on machine G to determine the effect of the C.P. flux upon the iron loss. Both the commutating poles and the main poles were separately excited, the iron loss being determined by measuring the input to the driving motor. The brushes of the machine under test were lifted, and correction was applied for the variation of the copper loss in the motor.

As the loss due to the C.P. flux was comparatively small and the supply voltage fluctuated a fair amount all the readings were repeated, the various points being indicated in the diagrams.

Curve A of Fig. 19 shows the input to the driving motor (after correction for copper loss) for different currents through the C.P. winding, the main poles being unexcited; and curve B shows the relation between the same quantities with full excitation on the main poles. It is evident from these curves that the iron loss due to the C.P. flux is independent of the polarity of the commutating poles relatively to that of

the main poles. Further, the two curves are so similar that we can conclude that the iron loss due to the C.P. flux is practically independent of the main-pole flux. Readings taken with a lower excitation on the main poles confirmed this conclusion.

The useful main-pole flux in the tests recorded in Fig. 19 was found to be 2·88 megalines, and the speed was maintained constant at 800 r.p.m. The corresponding flux density in the armature core is :—

$$B_a = \frac{2 \cdot 88 \times 1\,000}{290} = 9 \cdot 83 \text{ kilolines/cm}^2$$

From Fig. 19 the iron loss due to the main-pole excitation alone is 2 388 − 1 250 = 1 138 watts.

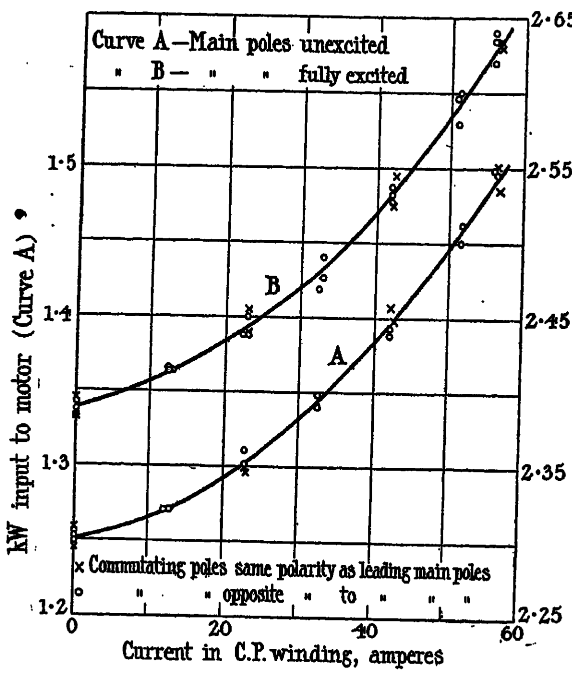

FIG. 19.

Hence from the expression on page 40 and the data in Appendix 1 we have

$$1\,138 = k \times \left(\frac{800 \times 2}{60}\right)^{1.5} \times (9 \cdot 83)^2 \times \left\{8\,920 + \left(\frac{290}{179 \cdot 2}\right)^2 \times 3\,340\right\}$$

$$\therefore k = 4 \cdot 7 \times 10^{-6}$$

At a flux of 2·26 megalines per pole the measured iron loss was 675 watts, and the corresponding value of k is $4 \cdot 56 \times 10^{-6}$. The average value of k may therefore be taken as $4 \cdot 6 \times 10^{-6}$.

Let us now see how the calculated values of the iron loss due to the C.P. flux compare with the measured values.

Full-load current of machine G = 85 amperes.

∴ Ampere-conductors per cm of periphery at full load = 191 and armature-turns per pole at full load = 2 480.

But ampere-turns per pole due to C.P. at full load

$$= 85 \times 44 = 3\,740.$$

∴ Net ampere-turns per pole acting on magnetic circuit of C.P. = 1 260.

Hence current through C.P. winding alone to produce same flux

$$\doteq 1\,260/44 = 28 \cdot 6 \text{ amperes.}$$

Let us therefore calculate the iron loss due to, say, 30 amperes through the C.P. winding alone.

Length of air-gap under C.P. = 0·30 cm (measured).

∴ Effective length of C.P. air-gap (see page 43)

$$= 0 \cdot 30 \times \frac{2 \cdot 66}{2 \cdot 66 - 0 \cdot 46 \times 1 \cdot 17} = 0 \cdot 376 \text{ cm.}$$

Flux density in C.P. air-gap

$$= \frac{30 \times 44}{0 \cdot 8 \times 0 \cdot 376} = 4\,390 \text{ lines/cm}^2.$$

∴ Flux density at mid-section of tooth

$$= 4\,390 \times \frac{\text{tooth pitch at tip}}{\text{average tooth width} \times 0 \cdot 9}$$

$$= 4\,390 \times \frac{2 \cdot 66}{1 \cdot 222 \times 0 \cdot 9} = 10\,600.$$

Axial length of C.P. shoe = 8·25 cm.

∴ Volume of teeth carrying C.P. flux

$$\doteq 3\,340 \times \frac{8 \cdot 25}{23 \cdot 5} = 1\,173 \text{ cm}^3.$$

Hence iron loss at 800 r.p.m.

$$= 4 \cdot 6 \times 10^{-6} \times \left(\frac{800 \times 2}{60}\right)^{1.5} \times (10 \cdot 6)^2 \times 1\,173 = 83 \cdot 8 \text{ watts.}$$

An estimate of the iron loss in the armature core due to the C.P. flux alone gave 1·8 watts, a negligible value compared with other losses.

The following table has been calculated on the assumption that the iron loss varies as the square of the current through the C.P. winding, and shows a fair agreement between the calculated and measured values.

Current in C.P. winding	Iron loss	
	Calculated	Measured
amperes	watts	watts
20	37·3	42
30	83·8	82
40	149	134
50	232	196

The application of these results has already been dealt with in Section 2 of the paper.

DIRECTIONS FOR THE STUDY OF NON-IGNITABLE AND SELF-EXTINGUISHING BOARDS AND MOULDINGS FOR ELECTRICAL PURPOSES.*

[REPORT (REF. A/S10) RECEIVED FROM THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION.]

CONTENTS.

PREFACE.

Experience has shown that materials which purport to possess non-ignitable or self-extinguishing properties vary greatly in their ability to withstand a high temperature and exposure to atmospheric conditions.

These Directions have been drafted to meet the need for suitable tests to determine the merits of the many materials of this class on the market.

The materials covered by this specification have more or less well-defined electrical insulating characteristics in addition to their non-ignitable or self-extinguishing properties.

A large amount of experimental work has been carried out in proving the methods of test given herein, and the results of these tests will be embodied in a Report to be issued later.

With a view to the determination of the effect of ageing, an investigation has been put in hand, details of which are given in Clause 19.

The Director of the E.R.A. will value comments and criticism from those who have occasion to use this Specification.

I. DEFINITIONS AND CLASSIFICATION.

(a) *Definition of non-ignitable.*

A " non-ignitable " material is one which when heated under certain prescribed conditions neither burns itself nor gives off inflammable vapours.

(b) *Definition of self-extinguishing.*

A " self-extinguishing " material is one which, under certain prescribed conditions, does not continue in a state of combustion in air after the removal of the external source of heat.

(c) *Classification of non-ignitable and self-extinguishing boards and mouldings.*

Class A.—This includes non-ignitable asbestos boards and mouldings made of asbestos fibre and a binder of soapstone or other similar natural clay. The material withstands repeated exposure to an electric arc in air or a flame of high intensity, and at the same time possesses relatively high insulating characteristics both with regard to electric strength and resistance to surface breakdown. This class includes material used for arc shields on control apparatus and the like.

Class B.—This includes non-ignitable asbestos boards and mouldings made of asbestos fibre and a binder of Portland cement, lime or similar material. The material withstands repeated exposure to an electric arc in air or a flame of high intensity, and at the same time possesses relatively high insulating characteristics, both with regard to electric strength and resistance to surface breakdown. This class includes material used for arc shields on control apparatus and the like.

Class C.—This includes non-ignitable asbestos boards and mouldings of a material that withstands repeated exposure to an electric arc in air or flame of high intensity, but does not necessarily exhibit high insulating characteristics. This class includes materials suitable for a large number of structural purposes and as barriers in oil switches, cubicles, and the like. The majority of so-called asbestos cements on the market fall within this class.

Class D.—This includes self-extinguishing asbestos boards and mouldings of a material that withstands

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the application of an electric arc in air or flame of high intensity for very short periods only, but possesses high insulating characteristics. This class includes the bitumen impregnated boards (frequently referred to as " Ebony " grades) which are suitable for terminal boards, relay boards, switchboards and the like.

Class E.—This includes asbestos millboard and similar materials made from asbestos fibre with the addition of a small amount of flexible binder. The material, although non-ignitable, is seriously affected with respect to its physical properties when subjected to repeated exposure to an electric arc in air or flame of high intensity.

NOTE.—It is to be understood that the classification of materials given above must be verified by the results of the tests outlined in this Specification.

II. METHODS OF TEST.

NOTE.—In view of the fact that individual specimens of the same material may vary greatly, it is necessary when determining a given property of the material to carry out tests on a sufficient number of specimens.

In the case of mouldings, the material for test shall be moulded into the form of a board not less than ¼ inch and not more than ½ inch thick, from which the specimens shall be cut.

1. CONDITIONING.

Before the tests specified in Clauses 2, 3, 4, 5, 6, 7, 8, 14, 15, 16, 17, and 18 are carried out the specimens shall be dried for 18 to 24 hours at a temperature from 75° C. to 80° C. for Classes A, B, C and E, and 40° C. to 45° C. for Class D. The test shall be conducted as soon as the temperature of the specimen has fallen to a value between 15° C. and 25° C.

2. DETERMINATION OF THICKNESS.

The specimen shall be conditioned in accordance with Clause 1 before the thickness is measured.

Measurements of thickness shall be made by means of a suitable micrometer at ten points equally spaced around the sides of the board. The maximum, minimum and mean values of thickness shall be stated.

3. DETERMINATION OF DENSITY.

The specimen shall be conditioned in accordance with Clause 1 before the density is determined.

A specimen 1½ inches square shall be used to determine the density of the material.

The area of the specimen shall be computed from the mean of five measurements of the length and the width respectively at points equally spaced along each of two edges at right angles. The thickness shall be determined by making ten measurements with a suitable micrometer equally spaced around the sides of the board, and the mean value shall be taken in computing the volume of the specimen.

The usual precautions shall be observed in weighing the specimen, and the weight shall be taken to the nearest milligramme.

The density shall be expressed in terms of weight in grammes per cm^3.

4. TENSILE STRENGTH, EXTENSION AND PLASTIC YIELD UNDER CONTINUOUS LOAD (NOT TO BE APPLIED TO CLASS E MATERIAL).

The specimen shall be conditioned in accordance with Clause 1 before the tests for tensile strength and extension are carried out.

The form and dimensions of the specimen shall be as shown in Fig. 1. The thickness of the test bar shall be the thickness of the material.

(*a*) The specimen shall be tested to ascertain the ultimate tensile strength and the extension on a 3-inch gauge length.

The load shall be increased steadily at such a rate that the specimen breaks in approximately two minutes from the time of the application of the load.

The ultimate tensile strength shall be expressed in lb. per square inch. The extension shall be expressed as a percentage on the original gauge length.

(*b*) The specimen shall be tested to ascertain the extension on a 3-inch gauge length when subjected

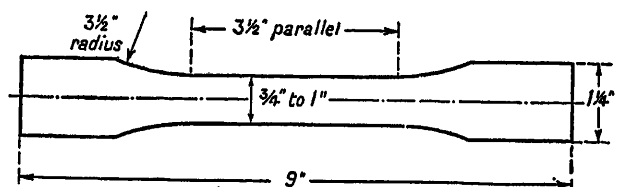


FIG. 1.—Specimen for Tensile Strength and Extension Tests.

continuously to a load of a value equal to one-third of the breaking load, determined by test (*a*). The load shall be maintained until the increase of strain ceases.

5. COMPRESSION STRENGTH (NOT TO BE APPLIED TO CLASS E MATERIAL).

The specimen shall be conditioned in accordance with Clause 1 before the compression strength test is carried out.

The dimensions of the specimen for test shall be 1 inch cube, the specimen being built up with several layers of the material when necessary. The layers of the material shall be bedded together by the application of an initial load of 300 lb. per square inch, and the first measurement of the length of the specimen shall be taken under this load, which shall be included in the load registered in each case.

A series of tests shall then be carried out at a temperature from 15° C. to 25° C. by the application of increasing loads of 1 500 lb. per square inch, each of which shall be maintained for one minute, and the yield of the specimen shall be measured at the end of each period. The tests shall be continued until the specimen has yielded 10 per cent of its original length, when measured as stated above, or the load has reached to about 6 tons per square inch.

6. SHEARING STRENGTH (NOT TO BE APPLIED TO CLASS E MATERIAL).

The specimen shall be conditioned in accordance with Clause 1 before the shearing strength test is carried out.

A specimen 5 inches long and 2½ inches wide shall be

clamped in a shear testing jig so that both ends of the specimen are sheared off simultaneously.

The load shall be applied steadily and shall be increased at a rate of approximately 100 lb. per minute for each 1/32 inch thickness of the specimen.

The pressure required to produce shear shall be computed on the total area of the sections sheared, and shall be expressed in lb. per square inch.

A suitable form of jig for the shear test is shown in Fig. 2.

200° C. to 205° C. for 24 hours, and shall then be subjected to an Impact Test as before, as soon as the temperature of the specimens has fallen to a value between 15° C. and 25° C.

8. Stiffness or Rigidity (not to be applied to Class E Material).

The specimen shall be conditioned in accordance with Clause 1 before the test for stiffness or rigidity is carried out.

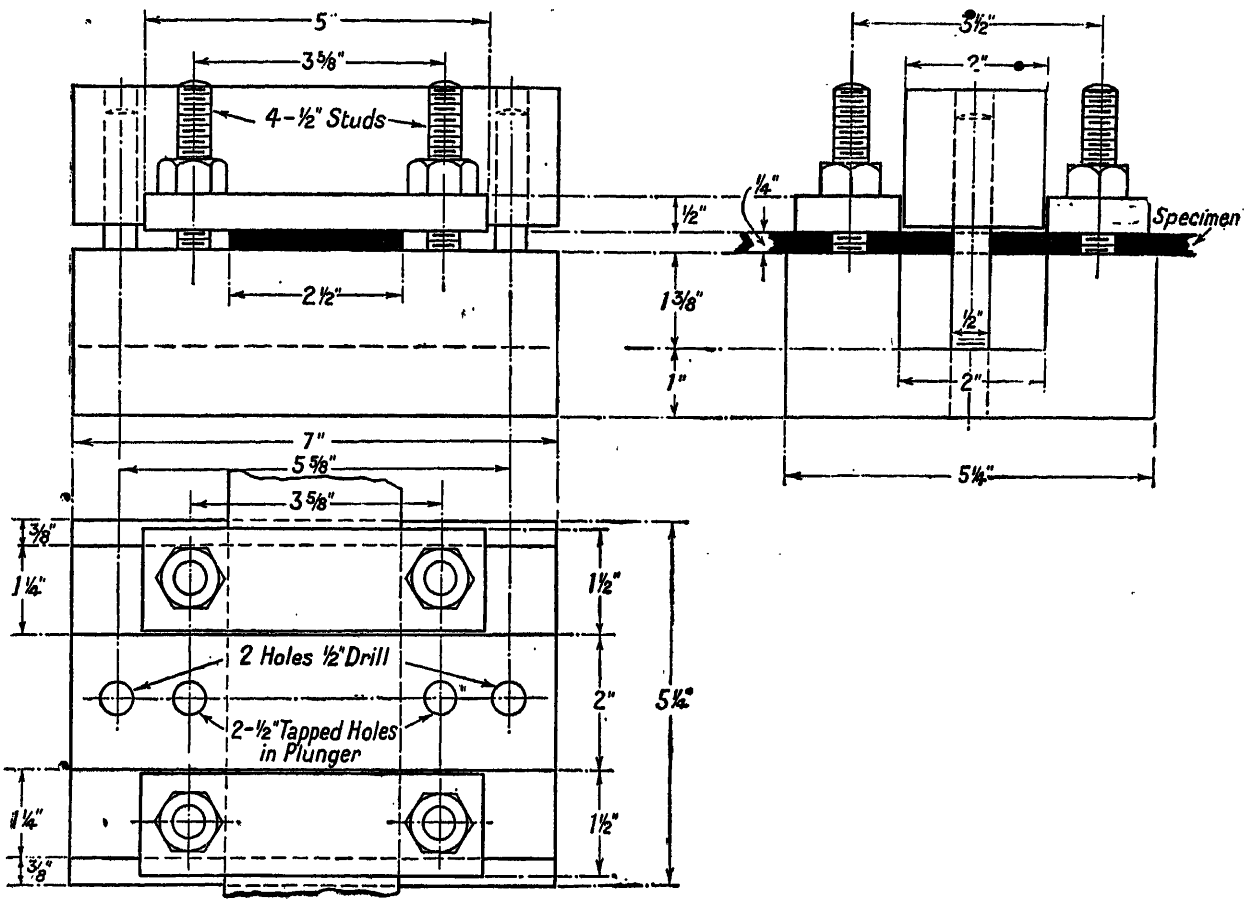


Fig. 2.—Form of Jig for the Shear Test.

7. Impact Test (Brittleness) (not to be applied to Class E Material).

The specimens shall be conditioned in accordance with Clause 1 before the impact test is carried out.

(a) Specimens 3 inches long and 2 inches wide shall be cut from the board. The thickness of the specimens shall be the thickness of the material.

The specimens shall be subjected to test in an impact testing machine of the Izod type. The natural surface of the material shall be in the plane at right angles to the direction of motion of the hammer.

The energy to cause fracture indicated by the machine shall be expressed in foot-lb. and the thickness of the specimens shall be stated.

(b) Specimens similar to those used in the test described above shall be heated at a temperature from

Materials shall be tested for stiffness or rigidity by the cantilever method as follows:—

(a) The form and arrangement of the test shall be in accordance with Figs. 3 and 4.

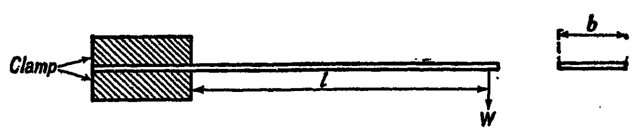


Fig. 3.—Form of Test for Stiffness or Rigidity.

The specimen shall be firmly fixed in clamps and the stirrup and scale pan placed in position as shown in Fig. 4. A measurement shall be made of the unsupported end below datum as follows:—

An inside micrometer shall be clamped above the

stirrup. The electric circuit shall be as shown in Fig. 4. The micrometer screw shall be turned until the circuit is closed (as indicated by the voltmeter) and the micrometer reading shall then be taken.

Small equal increments of load shall be applied and the corresponding increments in deflection measured immediately. Each increment of load shall be applied as soon as the deflection for the previous load increment has been read. Readings shall only be taken for the range during which the increment of load is proportional to the increment of deflection.

The dimensions of the specimen shall be as follows :—

The cantilever length shall be from 3 inches to 12 inches according to the stiffness of the material.

The breadth of the specimen shall be one-fifth of the cantilever length.

Young's Modulus E shall be computed from the following formula :—

$$E = \frac{4Wl^3}{bd^3y}$$

where W = average increment of load, lb.,
l = cantilever length, inches,
b = breadth of specimen, inches,
d = thickness of specimen, inches,
y = average increment of deflection, inches.

When the final increment of deflection has been measured as described above the load shall not be removed. The increment of deflection shall be re-measured after 1 minute, 10 minutes, 1 hour and 18 hours respectively.

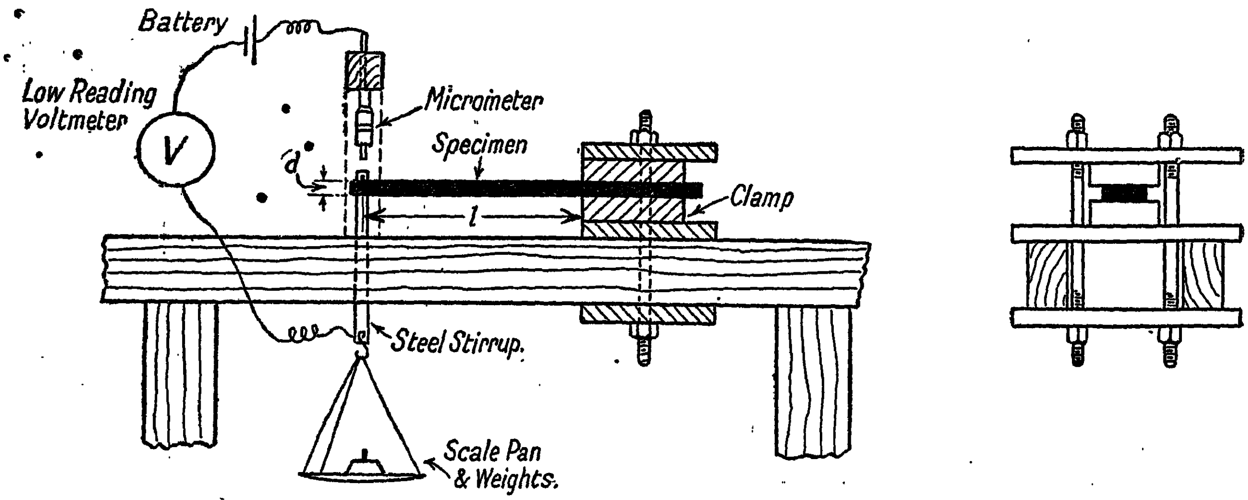


FIG. 4.—Arrangement of Cantilever Test.

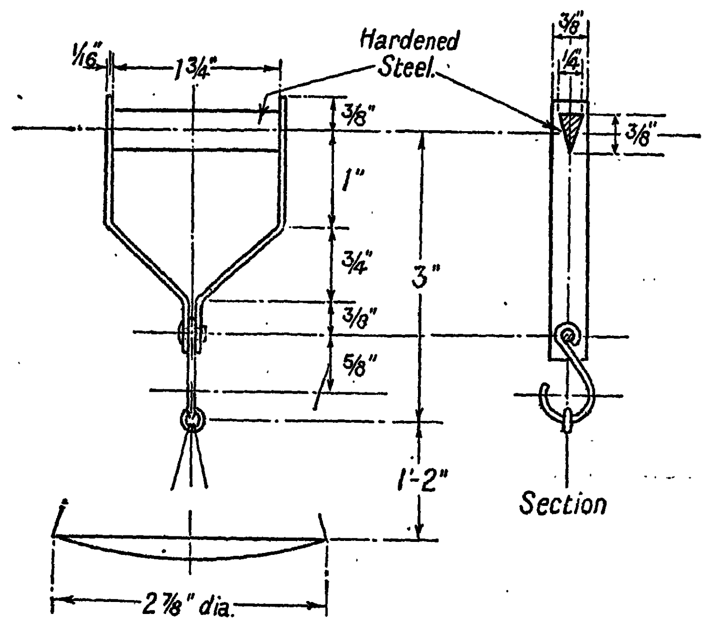


FIG. 5.—Form of Knife-edge Balance for Cantilever Test.

After the 18-hour test has been completed, tests at loads of 0·66 and 1·5 times the value of the load employed in the 18-hour test respectively shall be applied to the specimen, and the increments of deflection shall be re-measured as before in the prolonged test.

(*b*) Specimens similar to those used in the test described above shall be heated at a temperature from 200° C. to 205° C. for 24 hours, and shall then be subjected to a stiffness test as before, as soon as the temperature of the specimens has fallen to a value between 15° C. and 25° C.

NOTE:—A suitable form of knife-edge balance for use in the cantilever test is shown in Fig. 5.

9. ELECTRIC STRENGTH.

(*a*) *Conditioning of material.*

The electric strength test shall be carried out after the material has been subjected to the controlled atmospheres given below. The test shall be carried out whilst the specimen is in the controlled atmosphere in each case.

(i) *Normal condition.*

The specimen shall be subjected to a controlled atmosphere, relative humidity 75 per cent, at a temperature from 15° C. to 25° C. for 18 to 24 hours.*

(ii) *Damp condition.*

The specimen shall be subjected to a controlled atmosphere, relative humidity not less than 95 per cent, at a temperature from 15° C. to 25° C. for 18 to 24 hours.

(iii) *Hot condition.*

The specimen shall be subjected to a controlled atmosphere at a temperature from 180° C. to 185° C. for a sufficient period to ensure that the whole of the material has attained a temperature of 180° C.

(*b*) *Method of test.*

The output of the testing set shall be sufficient to maintain on the specimen the necessary potential difference for the maximum period required. The frequency of the potential difference shall be approximately 50 cycles, and if any other frequency is employed, its value shall be stated. The wave shape shall be as near sinusoidal as possible.

NOTE.—If the wave shape is not known to be satisfactory it should be checked whilst a specimen is under test and near the point of breakdown, and the necessary correction made to obtain R.M.S. values.

The potential difference should be regulated by means of a suitable resistance in series with the field of the alternator.

(*c*) *Electrodes.*

The upper electrode shall consist of a solid brass cylinder 1½ inches long and 1½ inches diameter. The lower electrode shall consist of a flat brass disc 3 inches diameter and ½ inch thick.

The sharp edges shall be removed from the electrodes but the radius of the edge shall not exceed 1/32 inch.

(*d*) *Method of expressing electric strength.*

A number of tests shall be carried out on each material to determine the potential difference required to puncture it after various periods from half a minute to such a time that the value of the potential difference is independent of the time. The results of the tests shall be plotted in the form of a time-voltage curve, and the electric strength in volts per mil at the end of one minute shall be computed.

* This value of relative humidity may be obtained by the use of a solution of calcium chloride in water, specific gravity 1·22 at 20° C.

10. SURFACE BREAKDOWN.

The surface breakdown shall be determined after the material has been subjected to the controlled atmospheres given below for 18 to 24 hours in each case.

The test shall be carried out whilst the specimen is in the controlled atmosphere.

Atmosphere.	Temperature, ° C.	Relative humidity, per cent
Normal	15 to 25	75 *
Dry	75 to 80	(See note below)
Damp	15 to 25	Not less than 95
Tropical	45 to 50	Not less than 90

NOTE.—To obtain the "Dry" atmosphere, air at an ordinary room temperature and humidity shall be heated to the temperature specified without artificial drying or humidifying.

The electrodes shall consist of either (*a*) two solid brass cylinders 1½ inches long and 1½ inches diameter, or (*b*) the electrodes specified for the electric strength test in Clause 9. The distance between the nearest surfaces of the two electrodes shall be 1½ inches in each case.

An alternating potential difference of 500 volts 50 cycles shall be applied between the electrodes, and shall be raised by increments of 250 volts each minute until the surface of the material indicates that an appreciable current is passing between the electrodes.

The highest potential difference reached in this test shall be recorded and, if practicable, a measurement made of the leakage current.

11. SHRINKAGE, WARPING AND SWELLING (NOT TO BE APPLIED TO CLASS E MATERIAL).

The tests for shrinkage, warping and swelling shall be carried out after the specimens have been subjected to a controlled atmosphere, relative humidity 75 per cent, at a temperature from 15° C. to 25° C. for 18 to 24 hours.*

(*a*) *Shrinkage.*

Shrinkage shall be determined as follows:

A specimen 4 inches square shall be cut from the material and the length, width and thickness measured after conditioning as specified above.

The length and width respectively of the specimen shall be the mean of ten measurements taken at points equally spaced along each of two edges at right angles.

The thickness of the specimen shall be the mean of ten measurements of thickness taken at points equally spaced around the edges.

The measurements shall be made by means of a micrometer or other suitable method.

The specimen shall be dried for 48 hours by heating

* This value of relative humidity may be obtained by the use of a solution of calcium chloride in water, specific gravity 1·22 at 20° C.

uniformly in an oven at a temperature from 105° C. to 110° C., and the length, width and thickness shall then be measured as before.

Comparison shall be made between the mean values of the dimensions before and after the heat treatment, and the percentage differences computed on the original mean values respectively shall be stated, the original mean values being given.

(*b*) *Warping*.

Warping shall be determined as follows:

A specimen 12 inches square shall be placed on a flat surface not less than 14 inches square, and a flat metal plate 12 inches square shall be placed on the specimen, so that the edges of the plate and the specimen coincide. The weight of the upper plate shall not exceed 1 lb. The distances between the four corners of the under surface of the upper plate and the corresponding points on the upper surface of the lower plate shall be measured.

The specimen shall be dried as specified in (*a*), then placed on the flat surface, and with the upper plate in position, the distances between the two surfaces shall be re-measured as before. Comparison shall be made between the sums of the four readings before and after drying, and the percentage increase computed on the sum of the original four readings shall be stated.

(*c*) *Swelling*.

Swelling shall be determined as follows:

The square specimen used in the shrinkage test shall be exposed to a jet of steam for six hours at a temperature from 105° C. to 110° C., and then the thickness shall be re-measured as before. Comparison shall be made between the mean thickness before and after the exposure to steam, and the percentage difference computed on the mean thickness after drying shall be stated.

12. Machining Properties (not to be applied to Mouldings).

The machining properties of material of Classes A, B, C and D shall be determined by sawing, shaping in a shaping machine and drilling with a drill of diameter equal to the thickness of the board.

In the case of Class E material, the sample shall be punched and cut with shears.

The effect on the material with regard to cracking, splitting, chipping or raggedness shall be stated.

13. Effect of Oil (not to be applied to Class D Material).

A specimen shall be immersed in mineral oil having a closed flash point not less than 250° C., for seven days continuously at a temperature from 200° C. to 205° C. The condition of the specimen after immersion shall be stated with respect to warping, splitting, swelling, blistering, softening or other deterioration.

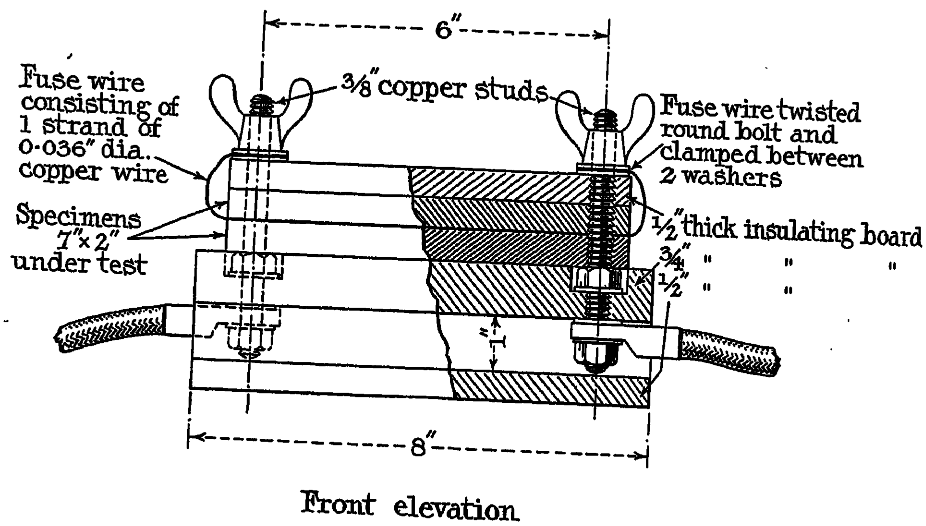


Fig. 6.—Arrangement of Fuse Wire Test.

14. Absorption of Water.

The specimen shall be conditioned in accordance with Clause 1 before the test for water absorption is carried out.

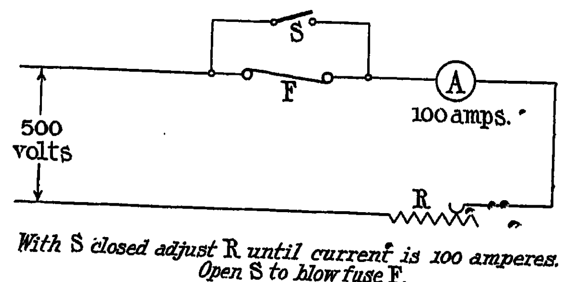


Fig. 7.—Diagram of Connections for Fuse Wire Test.

The dimensions of the specimen shall be 1½ inches square; and the four edges shall be freshly cut before the test is carried out.

The specimen shall be weighed and then immersed in water at a temperature from 15° C. to 25° C. After 24 hours' immersion it shall be taken from the water,

and, after removing the surface moisture by wiping, weighed again.

The specimen shall then be replaced in the water,

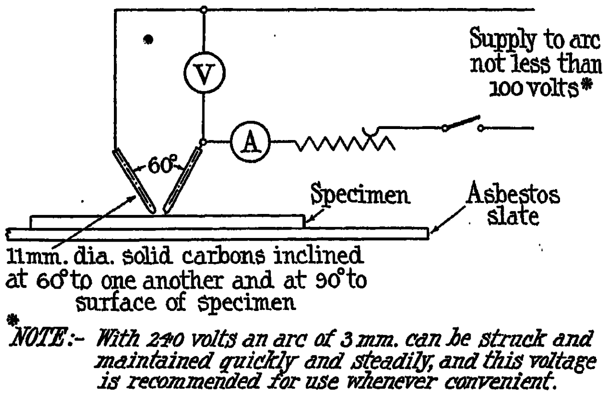


FIG. 8.—Arrangement of Carbon Arc Test.

and after six days' immersion re-weighed with the same precautions as before. The weight shall be taken to the nearest milligramme in each case.

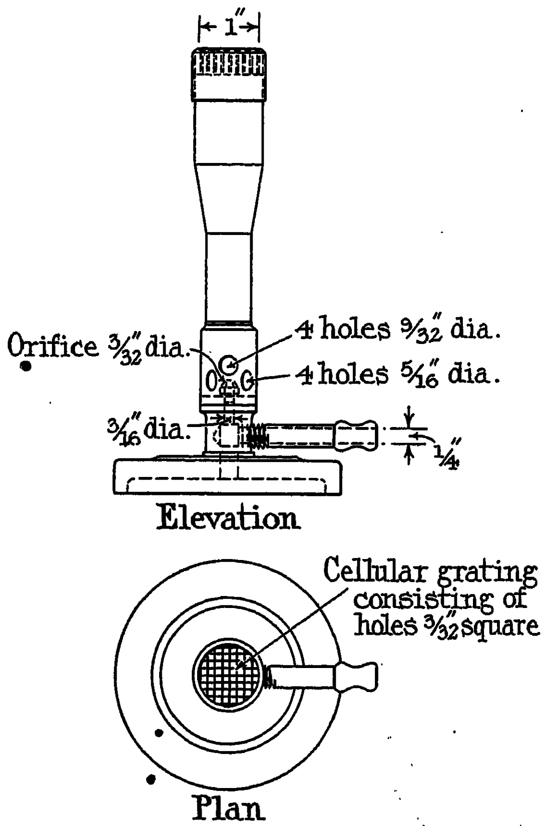


FIG. 9.—Dimensions of Méker Burner.

The percentage absorption of water in each case shall be computed on the original weight of the specimen; and the original thickness of the specimen shall be stated.

When it is desired to determine the absorption in the direction normal to the surface of the material, the edges of the specimen shall be coated with a waterproof varnish before the test for water absorption is carried out.

15. FUSE WIRE TEST.

The specimen shall be conditioned in accordance with Clause 1 before the fuse wire test is carried out.

The specimen shall consist of two pieces of the material each 7 inches long, 2 inches wide and not less than 3/16 inch thick, clamped together by two bolts 6 inches apart, the latter acting as terminals for the fuse wire. The fuse shall consist of a 0·036 inch diameter copper wire laid centrally between the two pieces of the material, the general arrangement being shown in Fig. 6. The wire shall be fused by being switched across a 500 volt d.c. circuit, in which there is a total non-inductive resistance of such a value as to limit the current to 100 amperes.

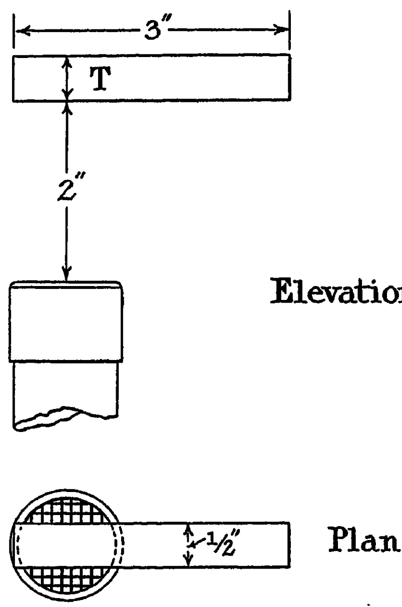


FIG. 10.—Arrangement of Méker Burner Test.

A convenient method for ensuring that the current through the fuse is of the required value is shown in Fig. 7.

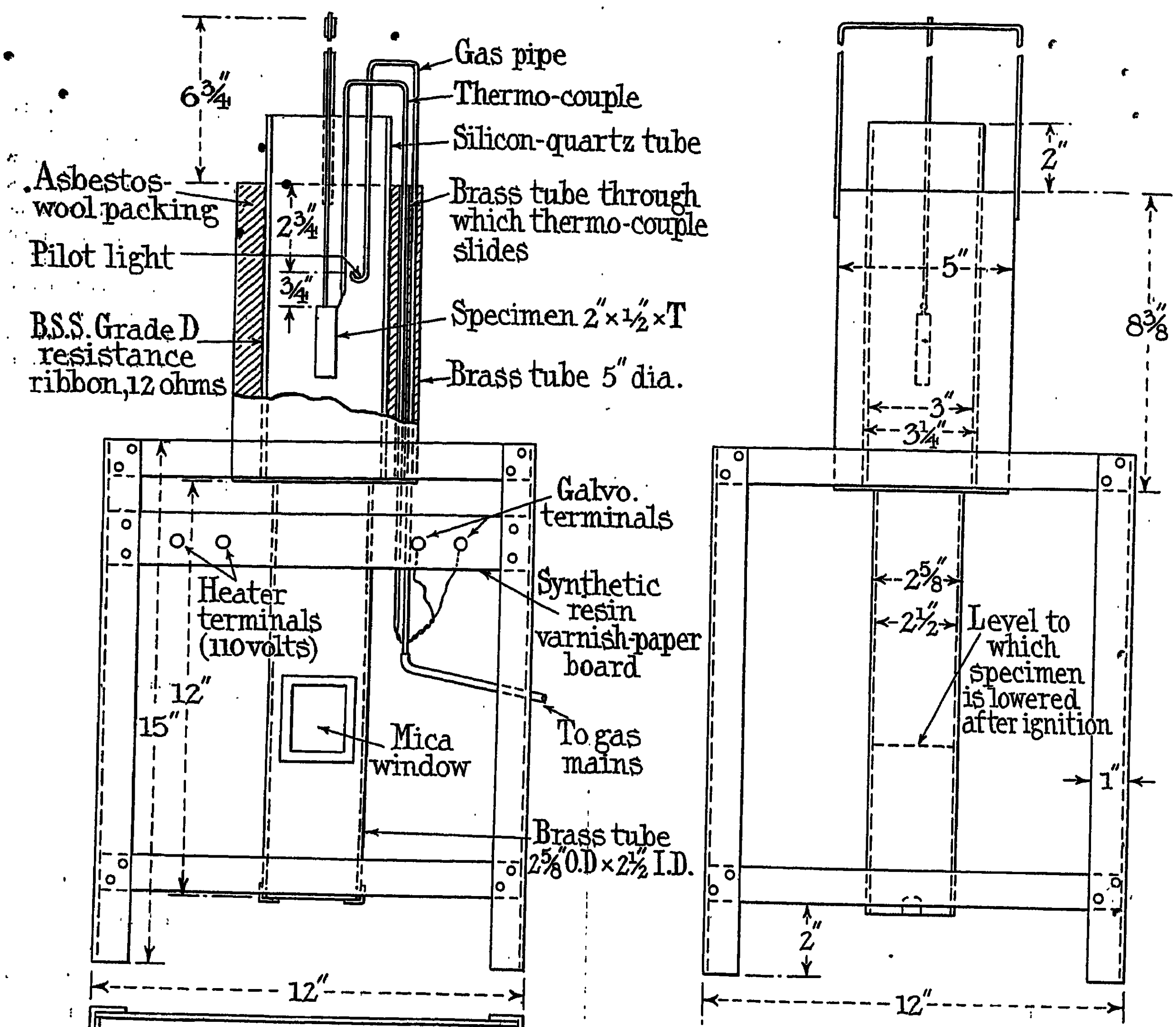
The test shall be repeated on the same specimen at intervals of two minutes until the material fails to extinguish the arc or its surface fuses, disintegrates or carbonizes. The number of times the fuse may be blown before this state is reached and the condition of the surface shall be recorded. If no disintegration has taken place after 10 tests, the condition shall be recorded at this stage.

For acceptance tests on materials for specific purposes the number of applications of the test which the material must withstand without showing a well-defined change shall be stated.

16. Carbon Arc Test.

The specimen shall be conditioned in accordance with Clause 1 before the carbon arc test is carried out.

Note.—When using material thinner than 3/16 inch for a given purpose, the sample tested should be of the thickness employed for that purpose.



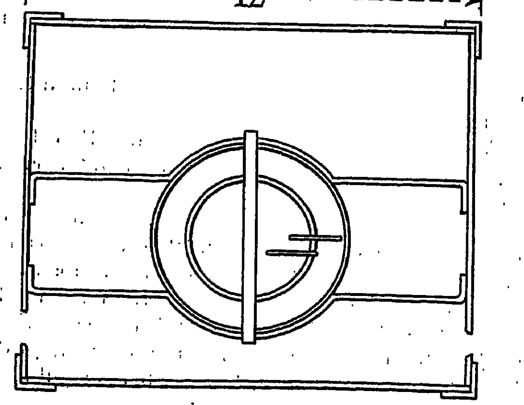


Fig. 11.—Arrangement of Radiant Heat Test.

The specimen shall consist of a flat sheet of the material. For testing the properties of a given material the sample shall be not less than 3/16 inch thick.

The specimen shall be placed on a horizontal base of asbestos slate or other similar heat-insulating material.

The arc shall be obtained between two solid carbons 11 mm diameter inclined at an angle of 60° to each other, with their plane set at an angle of 90° to the surface of the specimen, the carbons being arranged to travel just clear of the surface of the specimen. The arc is blown on to the specimen by the magnetic field established by the current in the inclined carbons.

The supply to the arc shall be connected through a switch, an adjustable resistance and an ammeter. A voltmeter shall be connected across the arc. The general arrangement of the test is shown in Fig. 8.

The carbons shall be operated by hand, the arc struck

and quickly adjusted to 10 amperes and 45 volts, being maintained steadily at this value, which corresponds to an arc length of approximately 3 mm. The effect of exposing the specimen to the arc for 15, 30, 60 seconds respectively, and if necessary for longer periods, shall be recorded.

For acceptance tests on materials for a specific purpose, the duration of applications of the arc shall be stated.

NOTE.—The mechanism and fittings of arc lamps sold for use in projection lanterns will be found suitable for the purpose.

17. MÉKER BURNER TEST.

The specimen shall be conditioned in accordance with Clause 1 before the Méker burner test is carried out.

The specimen shall consist of a piece of the material 3 inches long, $\frac{1}{2}$ inch wide and of thickness equal to the thickness of the material. The specimen shall be supported in the flame of a 1-inch Méker burner of the dimensions shown in Fig. 9. The specimen shall be placed with its axis horizontal and with the $\frac{1}{2}$-inch dimension facing the flame and 2 inches above the top of the burner, the end plane of the specimen being vertically above the edge of the burner as shown in Fig. 10.

The calorific value of the gas used must be known and shall be between 400 and 600 B.Th.U.'s per cubic foot.

The time before the specimen ignites shall be noted, and the constant K of the material shall be calculated from the following formula :—

$$K = \frac{TC}{500\,A}\left[\begin{array}{c}\text{Perimeter (inches) minus one horizontal}\\ \text{side (inches)}\end{array}\right]$$

where T = time in seconds before the specimen ignites,
C = calorific value of gas in B.Th.U.'s per cubic foot,
A = cross-sectional area of specimen in square inches.

18. RADIANT HEAT TEST.

The specimen shall be conditioned in accordance with Clause 1 before the radiant heat test is carried out.

The specimen shall be 2 inches long, $\frac{1}{2}$ inch wide, and of thickness equal to the thickness of the material, provided it is not more than $\frac{1}{2}$ inch thick. If the thickness of the material is over $\frac{1}{2}$ inch the specimen shall be cut down to $\frac{1}{2}$ inch thick.

The specimen shall be suspended in the apparatus shown in Fig. 11 so that its upper end is $5\frac{1}{2}$ inches below the top of the tube. The pilot flame shall be arranged $\frac{3}{8}$ inch above the upper end of the specimen. The air shutter shall be kept closed.

The temperature of the tube shall then be uniformly increased at a rate of 3 000° C. per hour and the temperature at which the material ignites shall be noted. When the material has ignited the specimen shall be lowered into the lower part of the apparatus to the level indicated in Fig. 11, and it shall be noted whether or not the material continues to burn. For this latter part of the test the air shutter shall be open.

NOTE.—If the apparatus is constructed to the dimensions and of the material indicated in Fig. 11 a constant current of about 9 amperes will give the correct rate of temperature rise.

19. AGEING.

NOTE.—The study of the effect of ageing on the materials covered by this specification is one of considerable importance, and boards of each class have been procured and are being stored in an ordinary atmosphere in an unheated building freely ventilated for periods of 6, 12, 18 and 24 months respectively.

To determine the effect of ageing the following investigation has been put in hand :—

The complete series of tests outlined in this specification is being carried out on representative materials at the commencement of the investigation, and will be again carried out at the end of two years. The following tests only will be made at the end of each six monthly period :—

Impact Test (Clause 7),
Carbon Arc Test (Clause 16),
Shrinkage Test as follows :—

A circle approximately 12 inches diameter to be inscribed on the sample, and the diameter measured accurately in the longitudinal and transverse directions respectively of the board, at the commencement of the investigation. The diameters of the circle to be measured again at the end of each of the six monthly periods, and the percentage shrinkage in the longitudinal and transverse directions respectively to be computed on the original values.

WIRELESS SECTION: CHAIRMAN'S ADDRESS

By E. H. Shaughnessy, O.B.E., Member.

(*Address delivered 5th November, 1924.*)

In my address last year* I gave particulars of the development of coupled circuits for arc transmitters of small power, and stated that the Post Office had decided to proceed with the installation of a coupled circuit for the 250-kW arc at Leafield. I am now able to say that we have completed and brought into commercial use the coupled circuit. To-day no trouble from "mush" or harmonics is observed and it is possible to receive broadcasting in close proximity to the station. The primary condenser is made of steel tanks containing 17 aluminium plates immersed in oil. Each unit has a capacity of 6 500 $\mu\mu$F, and four units are joined in parallel. The condenser contains 5 000 gallons of oil and weighs 25 tons. Under working conditions the condenser may handle as much as 260 amperes at 12 350 m. The working voltage (R.M.S.) is 68 000 (equivalent to a peak value of 96 000), and the energy handled is 18 000 kVA. The oil is cleaned and dried by a De Laval dehydrator and there has been no breakdown of the dielectric in use. The losses in the condenser are extremely small.

The primary coil is of copper strip made up in 8 flat spirals each containing 8 turns. The strip is carried direct on wooden spiders. The four lower spirals can be moved under the top four, the whole thus constituting a large variometer.

The coupling between the aerial circuit and the primary circuit is obtained by inserting a fixed coil of 4 turns of copper strip in the aerial circuit, and inside this a rotatable coil of 4 turns of copper strip which is connected to the primary circuit. This coupler is found to have a tendency to warm and is being replaced by one made of stranded wire.

It will be remembered that the examples which I dealt with last year were of coupled circuits applied to 25-kW and 40-kW arcs, and I mentioned that it had been found necessary to consume about 25 per cent more power than when the arcs were used on direct aerial circuits. It is therefore very interesting to note that with the 250-kW arcs at Leafield when used on 12 350 m there is no increase in the power consumed for the coupled circuit over that required for the plain aerial, while on 8 750 m the power consumption is actually less.

Typica lresults on 12 350 m are that with 237 kW input on plain aerial an aerial current of 254 amperes is obtained, whilst an input of 230 kW produces a primary circuit current of 220 amperes and an aerial current of 249 amperes.

Signalling is still done on the marking and spacing waves by varying the inductance of the primary circuit, the secondary or aerial circuit not being altered in tune.

* *Journal I.E.E.*, 1924, vol. 62, p. 51.

This is the largest coupled arc in existence working regularly and satisfactorily, and the constancy of the frequency is extremely good. The whole of the construction work was done by the Post Office Engineering Department and the arrangements are mainly due to Mr. A. J. Gill of that Department.

Aerial Tuning Coils.

It is generally understood that stranded wire is better for aerial tuning coils than copper strip, but, nevertheless, one sees copper-strip coils used and carrying several hundred amperes in high-power stations.

At the Northolt station a copper-tube coil was in use which had a very high resistance of about 3½ ohms. It was decided to replace this with a stranded-wire coil made up on wooden pancake spiders. The cable was made up of 729 strands of No. 33 S.W.G. enamel-insulated wire. When the cable was tested it was found that the insulation between wires and strands was faulty. It was decided to make up this cable into a coil and test its properties while a new length of similar cable with slightly thicker enamel insulation and silk insulation round each group of 81 wires was being manufactured.

When the faulty cable was made up into the coil and the spiders were adjusted to give an inductance of 1 680 μH its resistance was 2·05 ohms at a frequency of 43 kilocycles. A similar coil was then made with the new cable and when this was adjusted to have a value of 1 680 μH its resistance was only 0·776 ohm at 43 kilocycles. It will thus be seen that the insulation of the individual wires is a very important matter.

Table.

Decrements of Faulty and Good Cable.

Faulty cable		Good cable	
At frequency of		At frequency of	
20 kilocycles	40 kilocycles	25 kilocycles	50 kilocycles
0·0044	0·012	0·0044	0·0049

Tests on Dielectric Properties of Different Woods at High Frequencies.

Another matter of importance in the design of inductance coils for high-power stations is the selection of the material for supporting the cable, and an exhaustive test of various materials under high-

frequency stresses has shown that most of the insulating materials available tend to become hot and in many cases end in smoke under the prolonged application of high-frequency voltage. In the course of my address last year I showed samples of vitrified porcelain which had cracked and from which molten porcelain had oozed out, and I stated that good dry whitewood withstood the tests as well as anything else.

On the grounds of economy and also of ease of make-up, wood offers distinct advantages over other insulators for the manufacture of large inductance coils for use at radio frequencies. Unfortunately there appears to be no information available as to the properties of the various kinds of woods for this purpose, and accordingly, in order to obtain such information, samples of a number of different varieties of wood were obtained and subjected to a practical test.

The samples were all cut to a standard size, i.e. 1 in. × 1 in. × 4 in. long, and were arranged in a

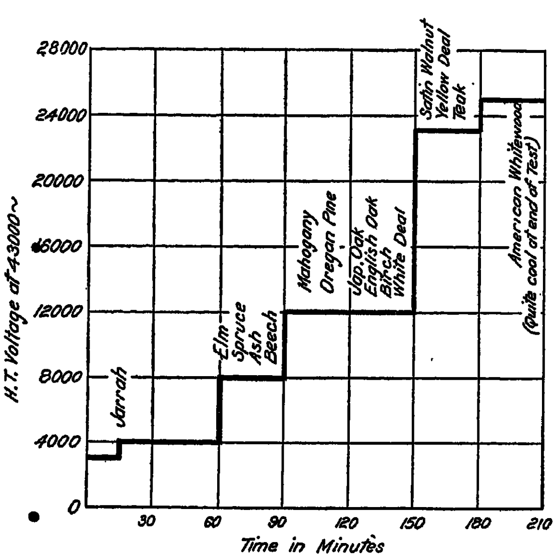


Fig. 1.

symmetrical manner between two copper plates connected across the tuning inductance of an arc oscillating circuit tuned to approximately 6 800 m.

The voltage was applied and increased gradually, until particular samples began to smoke and burn. These samples were then removed, and the voltage was further increased. Fig. 1 shows the steps in which the voltage was raised and the length of time during which each particular voltage was applied to the samples.

The point in the test at which each sample was removed on showing signs of failure is indicated by the point at which the name of the wood appears. It will be seen that the samples of American whitewood were superior to those of any other wood tested. Subsequent tests carried out on large numbers of samples of this wood at a voltage of approximately 35 000 amply confirm the results of these tests, and in no case has any charring or undue heating been observed.

In the case of one sample special arrangements were made to increase the voltage, and a flash-over occurred between the metal plates at 55 000 volts, the wood samples remaining undamaged.

Inductance coils have been made up using this kind of wood and have given every satisfaction under working conditions. Such a coil at Northolt radio station has proved itself capable of carrying a current of 115

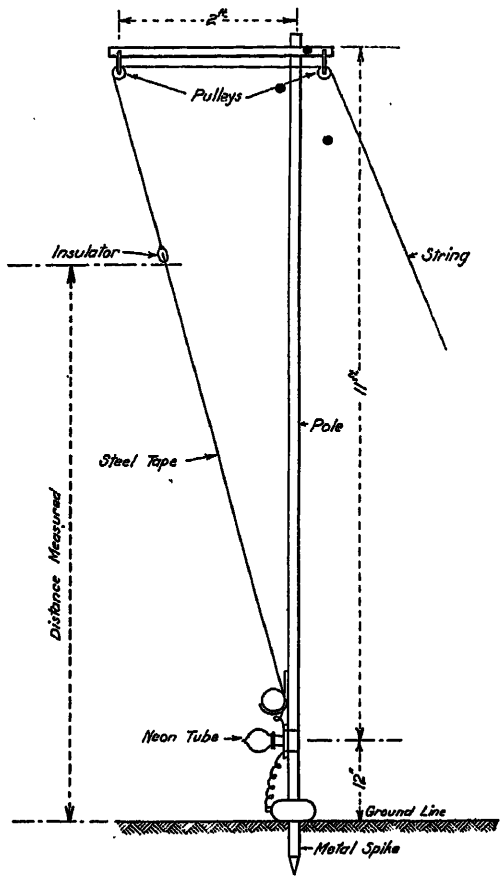


Fig. 2.

amperes, the voltage at the aerial end approximating to 60 000.

Method of Measuring the Electric Field under the Aerial.

So much has been written about the earth arrangements of various high-power stations that it would appear that very low resistance can be obtained from either elevated screen wires or buried earth wires led back on distributing elevated conductors with inductances inserted to balance the currents which each of these carries.

As a preliminary investigation into the character of these claims it was decided to explore the field under the aerial at Leafield. To this end the following experiment was carried out.

The fact that a neon tube, when held in a strong electric field with one electrode earthed and the other raised above the earth, glows when the potential drop

from the insulated electrode to earth equals the striking voltage of the tube, was used as the basis of the method of measuring the electric field. The strength of the electric field in volts per foot is obtained by dividing the striking voltage of the tube by the height in feet of the insulated electrode above the earth.

The apparatus devised for these measurements was as illustrated in Fig. 2. The neon tube was mounted 1 ft. from the base of a wooden pole 12 ft. long. One electrode was connected to the metal spike on the base of the pole, the other being attached to a steel tape which could be raised or lowered at will by means of a string passing over pulleys. The wooden cross-arm was necessary to prevent the tape from earthing on the pole, and also to minimize the capacity to earth between the tape and the pole.

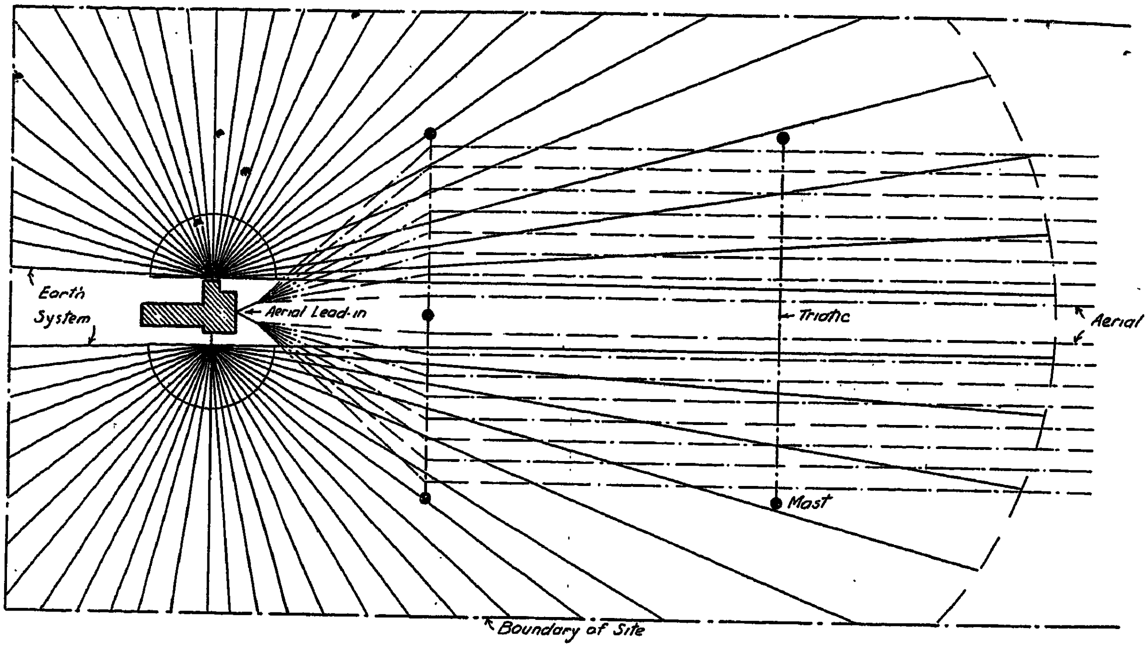


Fig. 3.

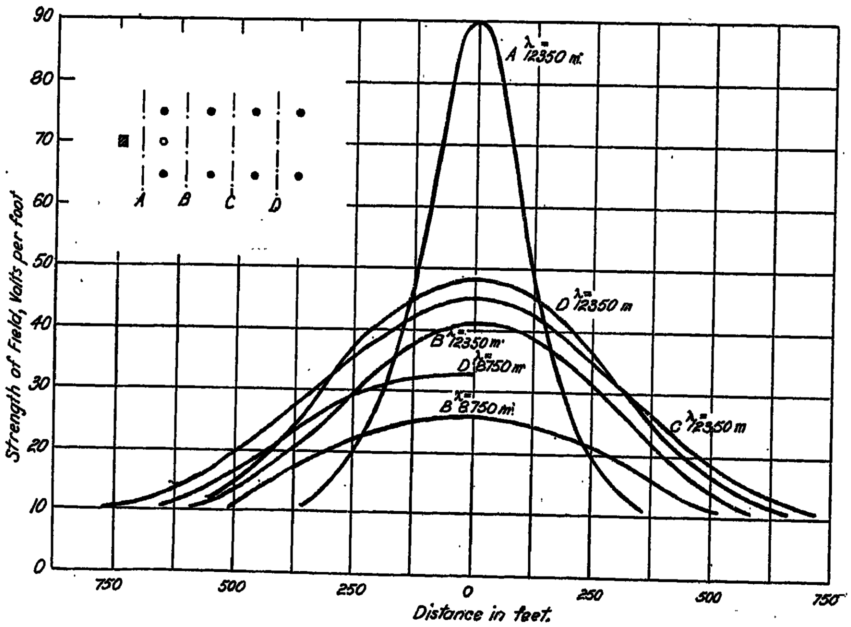


Fig. 4.

The method of making a measurement was as follows:—

The spike was driven into the ground, which sufficed to hold the pole in a vertical position. The observer

stood 4 paces from the pole and raised the tape until the tube commenced to glow intermittently and the keying could be read. The length of the tape which had been drawn out was noted, and the field strength was calculated as previously described. It was necessary for the observer to stand 4 yards from the pole, owing to his screening effect. At a shorter distance than this, when the tube was glowing any movement on the part of the observer towards the pole caused the light to go out.

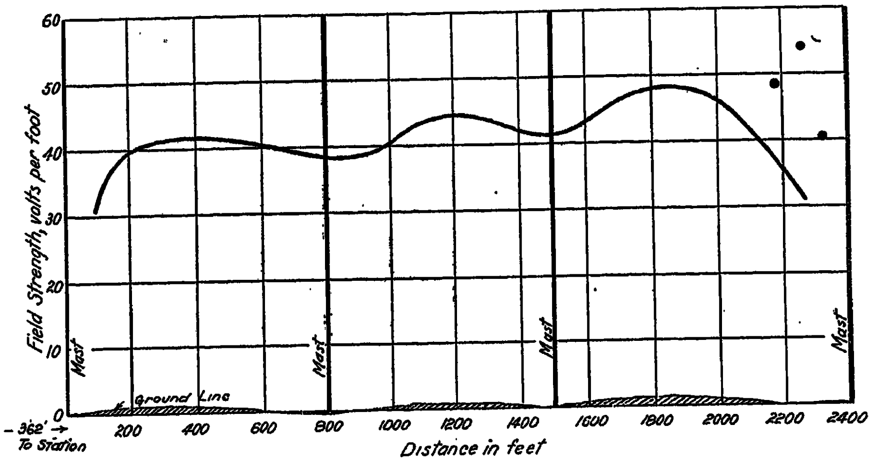


FIG. 5.

THE STRENGTH OF THE ELECTRIC FIELD UNDER THE LEAFIELD TRANSMITTING AERIAL.

The lettered dotted lines on the inset plan of the aerial system in Fig. 4 indicate the lines along which

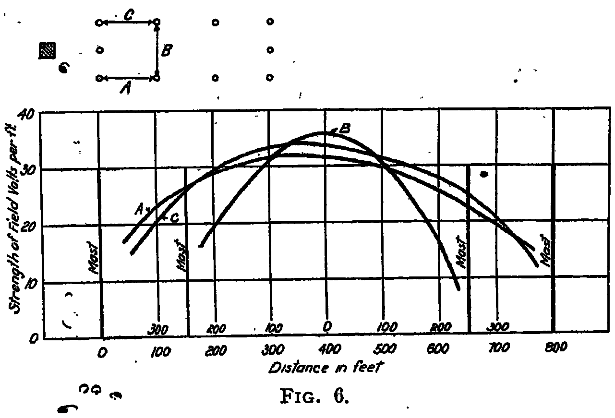


FIG. 6.

readings were taken, usually every 25 ft. The earth system, shown in Fig. 3, extends only so far as midway between the second and third pair of masts. From an inspection of the curves in Fig. 4 it will be observed that at a distance from the edge of the aerial equal to its height (300 ft.) there is a field of one-third the maximum intensity which occurs down the centre lines of the aerial. As would be expected, the field under the lead-in, curve A, is much stronger than elsewhere. It is apparent, therefore, from the curves B, C and D that the earth system has no appreciable effect on the distribution of the electric field under the aerial.

The curve in Fig. 5, taken down the centre line of the aerial, indicates a slight increase in the strength of the field towards the end furthest from the station. The effect of uneven ground on the field strength indicated that a rise in height of 5 ft., or 2 per cent of the total height of the aerial, caused a much greater percentage increase in the field strength.

The curves in Fig. 6 illustrate the screening effect of the masts and stays.

PROJECTED RUGBY STATION.

I should like now to say a few words about the Rugby station. The general design of this station is due to the Wireless Telegraph Commission, consisting of Dr. W. H. Eccles, Mr. L. B. Turner and myself, and the erection is being undertaken to this design by the Post Office Engineering Department.

The site is at Hillmorton, about 3 miles from Rugby, and is about 900 acres in extent. The wireless building is to be about the centre of the site. Twelve steel masts, 820 ft. high and spaced 1 320 ft. apart, are being erected. They are of lattice-steel construction, triangular in form with 10-ft. sides, and are being built by Messrs. Head, Wrightson and Co. of Thornaby-on-Tees. Each mast is supported on a ball-and-socket joint resting on a series of 12 porcelain insulators, the whole being supported on a granite block carried by a stanchion fixed to the foundations. A hoist is provided inside each mast with a platform at each position where stays are terminated, and there is also a continuous ladder from the bottom to the top. The mast is designed to stand a wind pressure of 60 lb. per sq. ft. of exposed surface and to support a horizontal load of 10 tons and a vertical load of 3 tons due to the antenna pull at the top.

The insulators are of special porcelain of flat circular shape, 8 in. diameter and $3\frac{1}{2}$ in. thick. Each insulator has to withstand a test pressure of 25 000 volts at 50 000 cycles per second for 6 hours without showing signs of heating and is, in addition, subjected to a test

load of 270 tons. Each mast will have three sets of five stays anchored at 200, 400 and 600 ft. Stays are made of 151 No. 10 S.W.G. wires laid up straight.

The aerial will consist of a continuous sausage of 12 ft. diameter, the supporting steel rope being carried down the centre of each mast and wound on a winch with slipping gear which will allow it to pay out when the tension exceeds 10 tons.

The primary circuit consists of a stranded wire cable inductance and Dubilier mica condensers. The aerial coil will also be of stranded cable. Three-phase power at 50 cycles per sec. and 12 000 volts is to be obtained from the Leicestershire and Warwickshire Electric Power Co.

Three motor-generators to give 6 000 volts each are arranged to be switched in series as required, so that any d.c. voltage up to 18 000 can be obtained. These machines are being made by the British Thomson-Houston Co. Water-cooled valves, each having an output of 10 kW and being made in this country by the Western Electric Co., will be used to make up the high-frequency generator.

General Review.

It is interesting to review the development of the art of radio engineering and to observe the influence of various workers in different parts of the world. In this country Marconi introduced the spark system with elevated aerial and connected earth system in 1896. Lodge in 1897 introduced the important principle of aerial tuning by means of a loading coil, and the Marconi Company's coupled-circuit spark system was developed so that, in 1913, spark stations dealing with about 300 kW were made. The Marconi Co. further developed the spark system so that, by timing the sparks, trains of waves were made to follow each other in correct phase and a continous-wave system was produced. The Stavanger station of about 200 kW power still works on this system. Suffice it to say that spark systems are now confined to small powers and special services such as ship and shore work.

In 1900 Duddell introduced the singing arc, which was developed by Poulsen for use at radio frequencies in 1903, and it is strange that very little development of this took place in Europe until after the Federal Telegraph Co. of America had built 100-kW arcs somewhere about 1912. During the war the arc was developed to modern sizes by the Federal Co., Mr. Elwell and others, and at present arcs having an output of from 200 kW to 1 000 kW are in commercial use.

In 1904 Fleming introduced the two-electrode valve as a detector; in 1907 De Forest introduced the third electrode into the valve and used an anode battery and found that the results obtained were better than with the two-electrode valve. Lieben and Reiss in 1911 showed an appreciation of the characteristics of a three-electrode valve by indicating how to use it for amplification without rectification. About the year 1913 Messrs. Round, Franklin, Armstrong, Langmuir and De Forest were investigating and developing the reaction properties of valves, and we know how rapidly these properties were adopted for use during the war for both sending and receiving. Valve sending stations up to an output of about 200 kW have been developed by the Marconi Co. in this country and by the American Telegraph and Telephone Co. in America.

In America Fessenden and Alexanderson proposed the construction of high-frequency alternators, and as far back as 1908 Alexanderson produced a 2-kW alternator which generated directly a frequency of 100 000 when running at 20 000 r.p.m. To-day the Telefunken Co. use high-frequency alternators with static frequency-changers, the Radio Corporation of America employ 200-kW Alexanderson alternators and the Société Française Radio-Electrique use Latour-Bethenod 200-kW and 500-kW alternators all running at reasonable speeds.

From this brief review it would seem that each of the four great companies has developed on its own lines, although I believe that a general interchange of the use of each other's patents is in operation.

The present practice of modern long-distance radio telegraphy has been the result of the efforts of many workers to establish the art on a basis where it can offer as good and speedy a service as any other form of communication, and in order to do that it is essential that ordinary telegrams should be sent over radio routes without any initial delay. It has been well known for many years that the ranges of stations are greater at night than during the day, and in order to extend the hours of reliable communication of the daylight hours—which are the business hours—higher powers and longer wave-lengths have been found to be more effective as the distances increased. These increases have certainly brought about improved results but have also appreciably increased the cost of erection of the aerial system of a high-power station. The cost of one 820-ft. mast may be anything from £12 000 to £15 000, and 12 such masts with aerial and earth systems complete may cost from £150 000 to £180 000. The total cost of a high-power world-wide station may be between £400 000 and £500 000, and in order to institute a service two stations are required. The interest and depreciation on these amounts are heavy annual charges and the total working expenses may amount to from £70 000 to £96 000 per station per annum, according to the amount of traffic dealt with.

To-day we have before us a choice of three systems for the internal equipment of high-power long-wave sending stations—by high-power I mean stations of over 200 kW—namely the high-frequency alternator, the Poulsen arc and the valve generator, and the art has not yet reached a stage where it can definitely be said which of these will best survive the test of time. The art of radio telegraphy is now about 30 years old and, as in the case of electric lighting and power, the monopoly due to fundamental patents has practically disappeared.

In view of the heavy cost of the aerial and earth systems the total cost of equipping a high-power station is not materially affected by the choice of any one of the above systems of internal sending plant. Speaking from experience, now that we have solved the problem of eliminating disturbances from the Poulsen-arc emissions, that system may be said to be by no means obsolete. It has advantages of its own in that it is very simple to work and maintain, can be started up

quickly and can have its working wave-length changed fairly rapidly.

Marconi, who, with Franklin, has been working with short waves since 1916, has recently described their latest development of the use of the beam system working on 92 m, and from his experiments concludes that with comparatively small powers and on short waves good communication can be obtained over extreme distances during the hours of darkness—an average of 7 hours per day—while over much shorter distances (2 670 miles) an average of 18 hours' communication per day can be obtained, the communication to be at the rate of 100 words per minute, exclusive of repetitions to secure accuracy.

The Post Office has entered into a contract with the Marconi Co. for the latter to provide a station to work to Canada as above at a cost of £50 420—the station to be capable of extensions to work to South Africa, India and Australia simultaneously, each extension costing £31 406.

It will be seen that, as the capital cost of these stations is low, depreciation and interest will be low and the power will also be comparatively low, but the cost of operating will depend upon the number of hours during which communication is satisfactory, and also upon the rate of working.

From our knowledge of the art it seems essential that high-power long-wave stations must be erected in order to provide for a full and regular Imperial telegraph service in which there shall be no initial delay due to ordinary telegrams having to be kept in hand until the favourable hours of working arrive, and also to be able to reach any and all parts of the Empire at any moment.

The erection of the short-wave beam stations will show to what extent they can assist in cheapening the cost of transmitting the less urgent forms of telegraph traffic and in reducing the number of high-power stations required in this country to meet the demands of a full Imperial radio-telegraph scheme.

INSTITUTION NOTES.

Honorary Member.

At the Ordinary Meeting of the Institution held on the 6th November the President announced that the Council had that day elected Sir Oliver Lodge, D.Sc., F.R.S., to be an Honorary Member of the Institution.

Summer Meeting, 1925.

The Council have accepted an invitation from the Chairman and Committee of the South Midland Centre for a Summer Meeting of the Institution to be held in the Midlands in June 1925. Full particulars will be announced later.

Norsk Elektroteknisk Forening.

At the request of the above Society the Council have agreed to the mutual granting of facilities and privileges as Visiting Members to members of the two societies visiting each other's country.

Members who intend to visit Norway and wish to avail themselves of this arrangement should apply to the Secretary of the Institution for a letter of introduction to the Norsk Elektroteknisk Forening, stating in what branch of the profession they are engaged and giving the name of the firm or company (if any) with which they are connected.

Gilbert's Treatise on the Magnet.

The Gilbert Club, which was recently wound up, was formed in the autumn of 1889 with the primary object of translating and publishing William Gilbert's classical work on the magnet, first published in Latin in 1600. Ten eminent scholars, including Mr. Latimer Clark, F.R.S., Sir Joseph Larmor, F.R.S., Prof. Meldola, F.R.S., and Prof. S. P. Thompson, F.R.S., undertook this work, which appeared in 1900. The title-page reads as follows:

> "William Gilbert of Colchester, Physician of London. On the Magnet, Magnetick Bodies also, and on the great magnet the earth; a new Physiology, demonstrated by many arguments and experiments. London, Imprinted at the Chiswick Press, anno MCM".

It is a page-for-page translation of the 1600 edition containing the numerous woodcuts, in facsimile, which appear in the original.

The edition, which was limited to 250 copies printed on hand-made paper, is a fine example of typography, and is bound in grey-blue boards with linen back.

On the winding up of the Club, it was decided to present its assets, consisting of a sum of £40 5s. 11d. and the last 34 copies of the treatise, to the Institution for the benefit of its Benevolent Fund. The Council are prepared to dispose of these volumes at a price of £5 5s. each, the full proceeds to be devoted to the Fund. In view of the small number of copies for disposal, members of the Institution are given the first opportunity of acquiring the work before it is brought to the notice of librarians. A copy is available for inspection in the Library of the Institution, and applications for copies should be addressed to the Secretary.

National Certificates and Diplomas in Electrical Engineering.

The following is a further list* of colleges, schools, etc., which have been approved under the scheme drawn up by the Board of Education and the Institution.

Approved for Ordinary Grade Certificates (Senior Part-time Course) :—

Birkenhead Technical School.
Bournemouth Municipal College.
Nelson Municipal Technical School.
Walsall Municipal Institute.
Wimbledon Technical Institute.

Approved for Higher Grade Certificates (Advanced Part-time Course) :—

Burnley Municipal College.
Gillingham Technical Institute.
Salford Royal Technical College—Apprentices' Day Course.

International Commission on Illumination.

REPORT BY LIEUT.-COL. K. EDGCUMBE ON THE CONFERENCE HELD AT GENEVA, 20–25 JULY, 1924.

Previous sessions.—The International Commission on Illumination held its first meeting in 1913 at Berlin, its second at Paris in 1921, the meeting at Geneva being the third.

Officers.—The present officers are as follows :—

President : Dr. E. P. Hyde (U.S.A.).

Hon. President : M. Th. Vautier (France).

Vice-Presidents : M. G. Semenza (Italy), Lt.-Col. K. Edgcumbe (Gt. Britain), M. Rouland (France).

Hon. Secretary and Treasurer : Mr. C. C. Paterson (Gt. Britain).

General Secretary : Mr. J. W. T. Walsh (Gt. Britain).

Constitution.—The constitution and working of the Commission are on similar lines to those of the International Electrotechnical Commission, except that the National Committee in each country is, by statute, constituted by a combination of the electrical interests, the gas interests and those of any society or body dealing particularly with illumination matters.

British National Committee.—The British National Committee is composed of five representatives from the Institution of Electrical Engineers, five from the Institution of Gas Engineers, five from the Illuminating Engineering Society and two from the National Physical Laboratory.

Delegates.—In the case of the British National Committee, the delegates to a plenary meeting are nominated by the representatives of each constituent Institution and are submitted to that Institution for approval. The nominees of the Institution of Electrical Engineers were Lt.-Col. K. Edgcumbe and Mr. P. Good. At the last moment, Mr. P. Good found it impossible to attend and, with the concurrence of the President, Mr. J. M. G. Trezise of the Post Office was nominated to fill the vacancy. The British delegation comprised five other members, in addition to Messrs. Paterson and Walsh who attended in their official capacities.

Other delegations.—In addition to Great Britain the following countries sent delegates : France, Italy, Japan, Poland, Switzerland and the United States of America. Belgium and Spain were unable to send representatives.

Proceedings at the meeting.—The subjects dealt with at the Conference may be grouped as follows :—

Nomenclature and symbols.
Photometry, with particular reference to the measurement of light differing in colour.
Standards of light.
Street and public lighting.
Lighting of schools and workshops.
Automobile headlights.
Industrial lighting generally.

A number of definitions were adopted, supplementing those agreed to in Paris in 1921. An International Committee was, moreover, set up to draft, in collaboration with the National Committees, an agreed vocabulary of terms used in the literature of illumination.

A comprehensive report on the subject of school and factory lighting was presented by the International Committee. Its recommendations were adopted and it was resolved that this report could usefully form the basis of any regulations which might be introduced in the various countries. It was strongly felt, however, that it was premature to lay down any legal minima.

The reports of the Motor Car Headlights Committees of France, Great Britain and the United States of America were closely studied, and it was agreed that to draw up any definite recommendations, in view of the present state of the industry, would be inadvisible. The International Committee was reappointed and all National Committees were asked to take up this question as an urgent matter, more particularly in view of the likelihood that an International Conference dealing with automobile matters might be summoned at an early date by the Governments concerned. Arrangements were discussed with a view to ensuring that the International Commission on Illumination should be effectively represented at any such conference.

The question of the education of engineers and the public generally in the advantages of good lighting aroused considerable interest, and it was agreed to allot to this subject an important place in the programme of the next meeting of the Commission.

Next meeting.—It was decided to hold the next plenary session of the Commission in 1927 in the United States of America.

Students' Visit to Lyons.

In August last the Students' Sections organized a visit to France at the invitation of the Société Française des Electriciens. It was decided to visit only one locality rather than travel from place to place as on previous occasions, and Lyons was chosen for the venue. Through the courtesy of Mr. J. Grosselin, Local Honorary Secretary of the Institution for France, and Mr. Dumont of the Société Française des Electriciens, a very attractive programme was arranged.

The party, numbering 26, left London on Sunday, 3rd August, arriving in Lyons the following morning, where they were met by Mr. Rivière, who acted as

* See *Institution Notes*, No. 39, p. 18; July, 1923 and *Journal I.E.E.*, 1924, vol. 62, pp. 209, 381 and 900.

guide to the party throughout the visit. The afternoon was spent in sight-seeing, after which the party visited the Lyons Fair, a large ferro-concrete building in which the Annual International Fair is held. The exhibits are arranged in three storys on each side of a central aisle, along which a rail track is laid for facilitating the installation of the exhibits. The visit concluded with a semi-official reception.

On the following morning a visit was paid to a Thury direct-current system operated by the Société Générale de Force et de Lumière, while the afternoon was occupied in an inspection of Mouche Central Station of the Compagnie du Gaz et de l'Électricité de Lyon, including a 70 000-volt outdoor transformer station.

On Wednesday morning the silk factory of Messrs. Vital Matthieu and Sons was inspected, after which the party was entertained by the Berliet Motor Company to lunch, followed by a tour of the works, where mass-production methods are employed.

On Thursday the party visited the Beaujolais vineyard, where they were entertained by the Société Française des Electriciens in the Château de Pizay.

On Friday there was an excursion to St. Etienne, where the 120 000-volt system of the Compagnie Électrique de la Loire et du Centre was inspected, followed by a visit to the coal mines of the Loire, the party being the guests of the company at lunch.

On Saturday morning an interesting visit was paid to the Lyons radio station. Saturday afternoon and Sunday were spent in individual expeditions to various local beauty spots, and the tour was brought to a conclusion by a farewell dinner at the Hôtel des Beaux Arts, at which a presentation was made to Mr. Rivière as a souvenir of a very enjoyable visit. A vote of thanks was also passed to Mr. J. H. Reyner, the Honorary Secretary of the London Students' Section, for his work in organizing the tour. The party left for London at 9.15 p.m.

The Committee wish to express their great appreciation of the courteous reception which they received everywhere in France, and, in particular, to the several firms and public bodies whose works they were privileged to visit. All who were present will carry with them a lasting memory of a very generous hospitality.

J. H. R.

Committees, 1924-1925.

Among the Committees appointed by the Council for 1924–25 are the following:—

Informal Meetings Committee.

The President.

Mr. A. H. Allen.
Mr. J. W. Beauchamp.
Mr. J. Coxon.
Mr. P. Dunsheath, O.B.E.
Mr. A. F. Harmer.
Mr. A. G. Hilling.
Mr. F. Pooley.
Mr. W. E. Warrilow.
Mr. H. T. Young.

Mr. F. Gill, O.B.E. (representing the General Purposes Committee).

The Chairman of the Papers Committee.

The Chairman of the London Students' Section.

Library and Museum Committee.

The President.

Col. R. E. Crompton, C.B.
Mr S. W. Melsom.
Mr. W. M. Mordey.
Col. T. F. Purves, O.B.E.

Local Centres Committee.

The President.

Mr. D. H. Bishop.
Mr. C. P. Coote-Cummins.
Sir J. Devonshire, K.B.E.
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Mr. F. Gill, O.B.E.
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Mr. J. S. Highfield.
Mr. T. B. Johnson.
Mr. D. G. Jones.
Mr. H. C. Lamb.
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Mr. A. Lindsay.
Mr. W. T. Maccall.
Mr. W. Nairn.
Mr. A. Page.
Mr. A. M. Paton.
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Mr. T. R. Smith.
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"Science Abstracts" Committee.

The President.

Mr. Ll. B. Atkinson.
Mr. F. Gill, O.B.E.
Mr. W. M. Mordey.
Mr. C. C. Paterson, O.B.E.
Dr. D. Owen .. } Representing the Physical Society
Mr. T. Smith .. } of London.

Ship Electrical Equipment Committee.

The President.

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And	*Representing*
Sir W. S. Abell, K.B.E. .. .. / Mr. H. Ruck Keene	Lloyd's Register of Shipping.
Mr. T. Carlton ..	Board of Trade.
Mr. W. Cross ..	Electrical Contractors' Association.
Mr. J. Foster King	British Corporation for the Survey and Registry of Shipping.
Mr. J. Lowson ..	Institution of Engineers and Shipbuilders in Scotland. Electrical Contractors' Association of Scotland.
Mr. A. W. Stewart	Institution of Naval Architects.
Mr. H. Walker, O.B.E. ..	N.E. Coast Institution of Engineers and Shipbuilders.

Wiring Rules Committee.

The President.

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Mr. H. J. Cash.
Mr. J. R. Cowie.
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And	*Representing*
Mr. B. M. Drake..	Contractors (unofficially).
Sir T. O. Callender Mr. J. F. W. Hooper	Cable Makers (unofficially).
Mr. A. C. Cockburn Mr. A. L. Taylor..	Fire Offices (unofficially).
Mr. E. G. Batt .. Mr. H. H. Berry.. Mr. J. R. Dick .. Mr. A. R. Everest Mr. C. Rodgers ..	British Electrical and Allied Manufacturers' Association.
Mr. W. F. Bishop	Cable Makers' Association.
Mr. F. R. Baldock	Independent Cable Makers' Association.
Mr. R. A. Ure ..	Electrical Contractors' Association of Scotland.
Mr. J. Christie .. Mr. F. W. Purse ..	Incorporated Municipal Electrical Association.
Mr. E. T. Ruthven Murray	Incorporated Association of Electric Power Companies.
Mr. W. R. Rawlings Mr. S. H. Webb ..	Electrical Contractors' Association.
Mr. J. M. Crowdy..	Association of Supervising Electricians.
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Dr. S. P. Smith.
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Electro-Chemistry and Electro-Metallurgy.

The President.

Mr. D. F. Campbell.
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Mr. S. E. Fedden.
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Sectional Committees—*continued.*

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Mr. C. W. Schaefer.
Mr. E. H. Shaughnessy, O.B.E.
Mr. F. Tremain.
Mr. H. T. Young.

Wireless Section.

The Committee of the Wireless Section for 1924-25 is constituted as follows:—

Mr. E. H. Shaughnessy, O.B.E. (*Chairman*).

The President.

Dr. S. Brydon.
Mr. R. C. Clinker.
Mr. C. F. Elwell.
Dr. J. Erskine-Murray.
Prof. C. L. Fortescue, O.B.E.
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Prof. G. W. O. Howe, D.Sc.
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Dr. R. L. Smith-Rose.
Mr. A. A. Campbell Swinton, F.R.S.
Mr. C. F. Trippe.

The Chairman of the Papers Committee (*ex-officio*).

And	*Representing*
Capt. C. E. Kennedy-Purvis, R.N.	Admiralty.
Major A. G. Lee, M.C., B.Sc. ..	Post Office.
Major H. P. T. Lefroy, D.S.O., M.C.	Air Ministry.
Major R. Chenevix Trench, O.B.E., M.C.	War Office.

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 October–25 November, 1924:—

	£	s.	d.
Bartlam, R. A. (Birmingham)		2	6*
Bell, Major H. (Hull)	1	1	0
Burge, W. S. (Bradford)	1	0	0
Clay, C. B. (Bromley)		10	0
Electric Carnival and Dance Committee (per Mr. W. A. Gillott)	38	12	4
Fippard, A. J. (London)	1	1	0
Hughes, E. L. (Liverpool)		8	6
Johnson, T. B. (Leeds)	3	3	0
North Midland Centre (per Mr. W. Howard Brown)	7	3	0
Orme, B. S. (Manchester)		5	0
Taylor, A. M. (Birmingham)		10	6
The "25 Club" (London) (per Mr. W. B. Esson)	15	15	0*
W. T. Henley's Telegraph Works Co., Ltd. (London)	25	0	0
Wright, H. Hodgson (Halifax)	1	1	0

* Annual subscription.

AN ELECTRIC HARMONIC ANALYSER.*

By J. D. COCKCROFT, R. T. COE, J. A. TYACKE, Students, and MILES WALKER, Member.

(*Paper first received 21st January, and in final form 22nd September*, 1924; *read before* THE INSTITUTION *6th November, before the* MERSEY AND NORTH WALES (LIVERPOOL) CENTRE *17th November, and before the* SCOTTISH CENTRE *9th December*, 1924.)

SUMMARY.

The paper deals with the experimental harmonic analysis of electromotive force and current wave-forms. A brief outline of existing methods is given and their limitations are discussed. A modification of the dynamometer method, which allows a much higher degree of accuracy to be attained, and in which the properties of an oscillatory circuit are used to obtain a sinusoidal current wave of suitable frequency, is described. This current is passed through one coil of a dynamometer, whilst the wave to be analysed is passed through the other. The values of the coefficients in the Fourier series representing the wave-form being analysed are obtained from the readings of the dynamometer and an ammeter.

The final method advocated aims at analysing wave-forms up to at least the 23rd harmonic and correct to within 0·1 per cent of the fundamental. The accuracy of the method must be established by comparison with a method more accurate than the commonly employed oscillograph method, the accuracy of which is considerably improved upon. Such a standard method, which involves the use of a synchronously driven commutator, is dealt with in detail in the first part of the paper and its own accuracy is established. Most of the principles involved are common to the two succeeding methods. A full discussion of the errors involved in the three methods is given, and the design of the necessary instruments is considered. For convenience, most of the mathematics involved is given in appendixes and only the results are quoted in the paper itself.

TABLE OF CONTENTS.

LIST OF CHIEF SYMBOLS USED IN THE PAPER.

r, r'' = total effective resistance of oscillatory circuit without and with valve amplification respectively.

r_1, r_2 = resistances of separate inductance coils in oscillatory circuit.

L = total inductance in oscillatory circuit.

L_1, L_2 = inductances of separate coils in oscillatory circuit.

C = capacity of condenser in oscillatory circuit.

R = total resistance of non-inductive potential divider shunting fixed coil of dynamometer.

R_1 = non-inductive resistance used between oscillatory circuit and commutator in standard method.

r_p, L_p = resistance and inductance respectively of dynamometer pressure-coil alone.

R_p, C_p = external resistance and capacity respectively in pressure-coil circuit.

Z_n = impedance of pressure-coil circuit to nth harmonic current.

$\omega = 2\pi \times$ (frequency of fundamental).

n = order of harmonic to which oscillatory circuit is tuned.

x = order of any other harmonic.

i_1 = instantaneous value of current in pressure coil of dynamometer.

I_n, I_x = amplitudes of nth and xth harmonics respectively in pressure-coil current i_1.

i_2 = instantaneous value of the current in fixed coil of dynamometer (i.e. of oscillatory current).

I'_n, I'_x = amplitudes of nth and xth harmonics in oscillatory current i_2.

I''_n, I''_x = amplitudes of nth and xth harmonics in oscillatory current, after amplification by means of valve.

V_n, V_x = amplitudes of nth and xth harmonics in resonating voltage across main inductance.

E_n, E_x = amplitudes of nth and xth harmonics in E.M.F. applied to oscillatory circuit by means of commutator or coupling with neon-lamp current.

α = one-quarter of phase angle corresponding to each impulse of neon-lamp current.

ψ = calculated error as fraction of fundamental.

δ = calculated error as fraction of harmonic being found.

ϕ_n, ϕ'_n = phase angles of nth harmonic currents in pressure coil and fixed coil respectively of dynamometer.

$\theta_n = \phi_n - \phi'_n$ = difference of phase between nth harmonic currents in the two coils of dynamometer.

N = ampere-turns (R.M.S.) of nth harmonic in fixed coil of dynamometer.

D = dynamometer constant, giving deflection in terms of ampere-turns of fixed coil and current of moving coil, i_1.

k = dynamometer constant, giving deflection in terms of i_1 and i_2, the currents in the two coils.

K = dynamometer constant, giving the nth harmonic in the E.M.F. applied to the pressure coil in terms of the dynamometer deflection and the resonating voltage (R.M.S.) across the fixed coil of the dynamometer.

K_1 = dynamometer torque constant.

E_{dc} = d.c. voltage applied to commutator.

M_1, M = mutual inductances between the neon-lamp circuit and grid circuit of valve, respectively, and the oscillatory circuit.

g, a, h, b, u = coefficients defining the valve characteristics.

i_a, v_a, v_g = anode current, anode voltage and grid voltage respectively of the amplifying valve.

A = amplification factor, or ratio of amplified to unamplified nth harmonic currents in oscillatory circuit.

e', v', d' = reading of voltmeter across E.M.F. supply being analysed, reading of voltmeter across fixed coil of dynamometer, and deflection of dynamometer respectively, all taken before amplification.

e'', v'', d'' = readings of instruments as above, all taken with amplified oscillatory current.

e_n = nth harmonic (R.M.S.) in the E.M.F. wave under analysis.

1. Introduction.

Those members of the Institution who have sat under the late John Perry will remember that one of the topics which he used to discuss with such infectious enthusiasm was the behaviour of a wattmeter of the dynamometer type when fed with currents of varying frequencies.

After a lecture on the Fourier series, illustrated by references to common everyday experiences, he arrived at the expression

$$\left.\begin{aligned} F(t) = A_0 + A_1 \sin\ \omega t + B_1 \cos\ \omega t + \\ \dots + A_2 \sin 2\omega t + B_2 \cos 2\omega t + \\ \dots + A_n \sin n\omega t + B_n \cos n\omega t + \end{aligned}\right\} \quad . \quad . \quad (1)$$

where $F(t)$ is any one-valued periodic function of time satisfying certain very general conditions which may be taken to hold in all cases likely to interest the electrical engineer; n is the order of a particular harmonic; and A_n and B_n are numerical coefficients. The full meaning of this expression was illustrated by examples drawn from physics and engineering.

He then introduced his students to the elements of harmonic analysis. Multiplying both sides of Equation (1) by $\sin \omega t$ and integrating throughout a complete period, that is from $\omega t = 0$ to $\omega t = 2\pi$ radians, we saw that all the terms on the right-hand side disappeared, except the terms containing $\sin \omega t$, so that

$$\int_0^{\frac{2\pi}{\omega}} F(t) \sin \omega t\, dt = A_1 \int_0^{\frac{2\pi}{\omega}} \sin^2 \omega t\, dt = \frac{\pi}{\omega} A_1$$

or more generally

$$\int_0^{\frac{2\pi}{\omega}} F(t) \sin n\omega t\, dt = \frac{\pi}{\omega} A_n$$

From this it is seen that any of the coefficients can be determined by the method of multiplying the function by $\sin n\omega t$, or $\cos n\omega t$ as the case may be, and integrating the product throughout a complete period.

He then pointed out that in the case of an electric current following a periodic function, $F(t)$, of the time, the process of multiplying and integrating could be carried out on a wattmeter of the dynamometer type. For if the current to be analysed is passed through the moving coil of a wattmeter while another current following the law $I_n' \sin n\omega t$ is passed through the stationary coil, the torque on the coil is at every instant equal to the product of $F(t)$ and $I_n' \sin n\omega t$, and the steady deflection of the coil gives the integrated value of all the instantaneous torques. Thus the deflection of the wattmeter is proportional to I_n' and to A_n. The constant of the wattmeter and the value of I_n' being known, A_n can be calculated.

Whether John Perry ever constructed an electric harmonic analyser on this plan is not on record. He no doubt recognized the initial difficulty of generating the analysing current $I_n' \sin n\omega t$ and keeping it accurately in phase, especially where the value of n is high. Many of his old students have no doubt wished for an opportunity to carry out the idea.

The advent of wireless telegraphy, and the familiarity which it has given us with swinging electric circuits, has brought just what was wanted for supplying the analysing current $I_n' \sin n\omega t$. For when an inductance of low resistance is placed in series with a capacity and the circuit is excited in a suitable way, the current in it naturally assumes the sine law, and there is no difficulty in making it of any desired frequency by choosing suitable values for L and C. Moreover, if the exciting pulses are controlled by the current to be analysed and the tuning is sufficiently close, the swinging current assumes the exact frequency of the impressed vibration and its phase is also under control, so that we have all the characteristics necessary for a successful analyser.

In this paper various methods of supplying the analysing current $I_n' \sin n\omega t$ are described. The advantages and disadvantages are discussed and the errors arising in the different cases are set out.

2. Consideration of Previous Methods.

Before proceeding to discuss the dynamometer method in full it will probably be of interest to summarize briefly the various methods of experimental harmonic analysis which have been proposed or described in the past.

These methods may be divided into two broad classes. The first class, which we may describe as "Indirect methods," consists of those methods in which the analysis is carried out in two distinct stages. The wave-form of the supply being analysed is first determined, so that the relation $e = F(t)$ can be expressed graphically; this wave-form is then analysed by one of the usual methods of approximate harmonic analysis.

Various methods of determining the wave-form exist. They depend in general on the Joubert contact principle or on the oscillograph.

Variations of the Joubert contact method have been

described in papers by Duncan,* Ryan,† Goldschmidt ‡ and Laws.§

In Duncan's and Ryan's method the current under analysis is passed through one coil of a dynamometer instrument, while a current is passed through the other coil only at that instant in each half cycle for which the reading is required. The latter current is controlled either by a synchronously driven commutator or by using a saturated transformer having a very sharply peaked secondary E.M.F., thus giving the necessary two impulses per cycle to the dynamometer.

In Goldschmidt's method the current under analysis is passed through one coil of a transformer whose magnetic circuit is completed for a short period in each half cycle. The measuring instrument is connected to a second coil on the core and may therefore be used to determine the values of the primary current at any desired point on the cycle. Laws's method is similar in principle.

In all these methods the duration of the impulse on the measuring instrument has to be made very small to obtain accurate values of the instantaneous E.M.F. The sensitivity of the instruments used is therefore much reduced and errors may be large.

The oscillograph may be considered to trace out the applied wave-shape sufficiently accurately, provided that the frequency of the highest harmonic under determination is not greater than one-tenth the natural frequency of the oscillograph. With the type of oscillograph generally in use, the error in the recording of a high-frequency tooth ripple might be of the order of 5 to 10 per cent.

Having determined the wave-form with sufficient accuracy the analysis may be carried out in three ways :—

(1) By Coradi or other type of mechanical analyser.
(2) By graphical methods.
(3) By calculation from measurement of selected ordinates.

A list of these methods is given in the bibliography to the paper. A general discussion of their accuracy was given by A. E. Clayton in a recent paper.‖ In general it may be stated that the probable accuracy of the "indirect method" of harmonic analysis cannot be greater than 1 per cent of the fundamental term.

The second class of methods, the "Direct methods," determine the values of the coefficients directly from the readings of one or more instruments. We shall discuss three of these methods.

(1) *Resonance Methods.*¶

This method consists generally in applying the E.M.F. under analysis to a circuit containing a choke coil and a condenser in series. By tuning the circuit so that resonance occurs with any particular harmonic, and measuring the voltage across either the choke coil or condenser, the value of the harmonic to whose frequency the circuit is tuned may be calculated, if the constants of the circuit are known.

The chief errors in this method are due to :—

(*a*) The readings obtained for one harmonic being influenced by the other harmonics, in particular by those harmonics whose orders are nearest to that of the harmonic under measurement. To reduce this interference to a negligible amount it is necessary to construct a choke coil with a very low damping factor, the ratio of self-induction to *effective* resistance being not less than 0·1. This necessitates using an iron-cored coil or a large weight of copper (of the order of 200 lb.).

(*b*) Having obtained this low damping factor, difficulty arises in obtaining accurate readings for the peak values of current, due to small variations from exact resonance frequency. Thus a variation of 0·5 per cent from exact resonance frequency would mean a decrease in resonating current to one-sixth of the peak value, when determining the 21st harmonic of a 50-cycle wave.

(*c*) The effect of eddy-current losses in iron and copper and of hysteresis losses in iron and dielectric. These cause a change in effective resistance with frequency and, since the E.M.F. across the coil varies inversely as the *effective* resistance, serious errors are introduced. For accuracy, the circuit has to be calibrated for the whole range of frequencies.

(2) *Rectifying Methods.*

This class of method has been fully treated in papers by Lyle,* Bedell † and Labouret.‡ They depend on the same principle as Fischer-Hinnen's method of approximate analysis by selected ordinates (see Bibliography). If i_t be the instantaneous value of current at time t, and T be the period of the wave, we have

$$\begin{aligned} i_t &= I_0 + I_1 \sin(\omega t - \phi_1) + I_2 \sin(2\omega t - \phi_2) \\ &\quad + \ldots I_n \sin(n\omega t - \phi_n) \ldots \\ i_{t+T/(2n)} &= I_0 + I_1 \sin\{\omega[t + T/(2n)] - \phi_1\} \\ &\quad + I_2 \sin\{2\omega[t + T/(2n)] - \phi_2\} \\ &\quad + \ldots I_n \sin\{n\omega[t + T/(2n)] - \phi_n\} + \ldots \end{aligned}$$

and it may easily be shown that

$$\begin{aligned} & i_t - i_{t+T/(2n)} + i_{t+2T/(2n)} - i_{t+3T/(2n)} + \ldots \\ & \quad - i_{t+(2n-1)T/(2n)} = 2n[I_n \sin(n\omega t - \phi_n) \\ & \quad + I_{3n} \sin(3n\omega t - \phi_{3n}) \\ & \quad + \ldots I_{kn} \sin(kn\omega t - \phi_{kn}) + \ldots \end{aligned}$$

i.e. the sum of the series

$$i_t - i_{t+T/(2n)} + i_{t+2T/(2n)} + \ldots \quad (2)$$

will depend only on the harmonics of order n, $3n$, $5n$, etc.

The methods described in the above-mentioned papers perform the summation (2) mechanically by means of a synchronously driven commutator. If therefore the

* *Transactions of the American Institute of Electrical Engineers*, 1892, vol. 9, p. 179.
† *Ibid.*, 1899, vol. 16, p. 365.
‡ *Elektrotechnische Zeitschrift*, 1902, vol. 23, p. 496.
§ *Proceedings of the American Academy of Arts and Science*, 1901, vol. 36, p. 321.
‖ *Journal I.E.E.*, 1921, vol. 59, p. 491.
¶ BLONDEL: *Elektrotechnische Zeitschrift*, 1906, vol. 27, p. 693; *L'Éclairage Électrique*, 1907, vol. 52, p. 441. See also R. BEATTIE: *Electrician*, 1912, vol. 69, p. 63, and vol. 67, pp. 326, 370 and 444; also *Revue Électrique*, 1912, p. 171. See also bibliography at the end of the paper.

* *Philosophical Magazine*, 1903, vol. 6, p. 549.
† *Electrical World*, 1913, vol. 62, p. 378.
‡ *Revue Générale de l'Electricité* 1921, vol. 9, p. 360.

highest appreciable harmonic is of order xn, in the determination of the nth harmonic the amplitudes and phase angles of the harmonics of orders $3n$, $5n$, . . . xn have to be determined. The commutator has therefore to be capable of reversing the direction of current xn times per cycle.

It will be seen that for the determination of one particular harmonic this method is very laborious.

(3) *A Potentiometer Method.**

The alternating-current potentiometer is used for the analysis. If the phase of one of the currents in the potentiometer circuit be shifted by 120° from the phase giving no deflection in the vibration galvanometer, a current will flow due to all the harmonics except the 3rd, 9th, 15th, etc., assuming the even harmonics to be negligible. Similarly by shifting the phase by 72° the harmonics of order $5n$ will produce no effect. Hence by taking a number of readings with different settings of the phase shifter, it is possible to establish a series of equations with the amplitudes of the harmonics as unknowns and on solving these to determine these amplitudes.

The method is not very accurate, since the potentiometer is not being used in a nul method, and in addition the calculation becomes very cumbersome if the order of harmonic which it is desired to determine much exceeds the 13th.

3(a). Theory of the Dynamometer Method.

The simplest direct method, from the theoretical point of view, is undoubtedly the dynamometer method. As we have shown in the introduction, the current to be analysed, or a current proportional to the E.M.F. if an E.M.F. wave is to be analysed, is passed through one coil of a dynamometer, whilst an "analysing" sinusoidal current of the frequency of the harmonic to be found is passed through the other coil.

Let the current under analysis be denoted by i_1, and the analysing current by i_2, and let

$$i_1 = I_0 + I_1 \sin(\omega t - \phi_1) + I_2 \sin(2\omega t - \phi_2) + \ldots I_n \sin(n\omega t - \phi_n)$$

and
$$i_2 = I_n' \sin(n\omega t - \phi_n')$$

Then the instantaneous torque on the moving coil is

$$\begin{aligned}\tau &= K_1 i_1 i_2 \\ &= K_1 I_n' \sin(n\omega t - \phi_n')\{I_0 + I_1 \sin(\omega t - \phi_1) + \ldots \\ &\qquad + I_n \sin(n\omega t - \phi_n) + \ldots\}\end{aligned}$$

If now the natural period of the instrument is large compared with the period $2\pi/\omega$, the deflection d will be proportional to the mean torque and is given by

$$\begin{aligned}d &= k\frac{\omega}{2\pi}\int_0^{2\pi/\omega} I_n' \sin(n\omega t - \phi_n')\{I_0 + I_1 \sin(\omega t - \phi_1) \\ &\qquad + \ldots I_n \sin(n\omega t - \phi_n) + \ldots\}dt \\ &= \tfrac{1}{2}kI_nI_n' \cos(\phi_n - \phi_n') \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)\end{aligned}$$

Thus, k and I_n' being fixed, the deflection depends only on the amplitude of the harmonic in the complex wave having the same frequency as the analysing current. By controlling the phase of the analysing current, ϕ_n' can be varied until d is a maximum, which occurs when $\phi_n = \phi_n'$. I_n' is measured and k is known; hence I_n may be calculated.

Alternatively, we may alter the phase of the analysing current by a quarter of a cycle and obtain a new deflection

$$d_0 = \tfrac{1}{2}kI_nI_n' \sin(\phi_n - \phi_n') \quad . \quad . \quad . \quad (3a)$$

From (3) and (3a) we may eliminate $(\phi_n - \phi_n')$ and determine I_n.

Thus
$$I_n = \frac{2\sqrt{(d^2 + d_0^2)}}{kI_n'} \quad . \quad . \quad . \quad . \quad (3b)$$

If the analysing current does not coincide exactly in frequency with any harmonic and is given by

$$i_2 = I_n' \sin\{(n\omega - \sigma)t - \phi_n'\}$$

where σ is small compared with ω, we have for the torque on the moving system

$$\begin{aligned}\tau = \tfrac{1}{2}K_1 I_n I_n' [&\cos(\sigma t + \phi_n' - \phi_n) \\ &- \cos\{(2n\omega - \sigma)t - (\phi_n' + \phi_n)\}] + R_n\end{aligned}$$

where R_n contains only terms of periodicity higher than or equal to $(\omega - \sigma)$. The only term influencing the deflection will therefore be that involving σt, and therefore

$$d = \tfrac{1}{2}kI_nI_n' \cos(\sigma t + \phi_n' - \phi_n) \quad . \quad . \quad (3c)$$

k being unchanged, provided σ is small compared with the natural periodicity of the moving system. The deflection will therefore vary harmonically with period $2\pi/\sigma$, and from observations of the maximum deflection we might determine I_n.

The difficulty in practice is to obtain a perfectly sinusoidal current of suitable frequency. We therefore proceed to discuss the error introduced by the analysing current not being exactly sinusoidal.

3(b). The Errors Introduced by an Imperfect Analysing Wave.

For a correct appreciation of these errors it is necessary to discuss briefly the probable size of the coefficients we are measuring.

In the first place we know from observations by means of an oscillograph that the wave-forms of most alternating-current generators are roughly sinusoidal and that the amplitude of the harmonics is considerably less than the amplitude of the fundamental, except in very special cases when the harmonics have been exaggerated by resonance.

The smallness of the amplitude of the harmonics arises from the effort of the designer of the machinery to suppress them as much as possible, and in this effort he is greatly aided by the following circumstances:—

Most alternating-current machines have north and south poles of similar conformation, so that the positive lobe of the wave-form is the same shape as the negative lobe. When they are identical the even harmonics disappear altogether and we are left with only the odd

* Quattrosoldi: *L'Elettrotecnica*, 1915, vol. 2, p. 616.

harmonics. That is to say, in most cases n has only odd values and

$$e = E_1 \sin(\omega t - \phi_1) + E_3 \sin(3\omega t - \phi_3) + \ldots$$

In the next place, the shape of the field-form of most a.c. machines is roughly sinusoidal, so that if the flux density B in the gap at any point is expressed as a function of the angular position, θ, of the point (taken as a two-pole machine)

$$B = B_1 \sin(\theta - \psi_1) + B_3 \sin(3\theta - \psi_3) + \ldots$$

it will be found that, upon the whole, the higher harmonics of B have smaller and smaller amplitudes as their order increases. For instance, if we take the case of a rectangular field-form (and most field-forms in practice are a good deal more favourable than the rectangular form), we have

$$\frac{B_n}{B_1} = \frac{1}{n}$$

Where, however, there are teeth upon the field magnet, as in the case of some turbo-generators, some of the higher harmonics in the field-form may be more pronounced.

A further cause of the smallness of the higher harmonics in the E.M.F. wave-form is the spread of the coils on the armature of the a.c. machine. The effect of the spread is usually expressed by means of the "breadth coefficients" or "distribution factors," f_1, f_3, f_5, corresponding to the various harmonics. With a perfectly distributed winding, we get as the general expression for the distribution factor

$$f_n = \frac{\sin n\sigma}{n\sigma}$$

where σ is half the angle of the coil spread. The value of this becomes rapidly smaller and smaller as n is increased. Where, however, the winding lies in m slots whose angular spacing is γ, the general expression for the distribution factor becomes

$$f_{ns} = \frac{\sin nm(\gamma/2)}{m \sin n(\gamma/2)}$$

For most values of n this expression becomes smaller as n is increased, but in the special case where there are Q slots per pole (Q being an integer) and $n = 2KQ \pm 1$, the value of the distribution factor becomes equal to the distribution factor for the fundamental. By making Q fractional, this condition can be avoided. If this is inconvenient in the design of the machine, care is usually taken to make B_n very small for the harmonic in question. As the amplitude of the harmonic in the E.M.F. wave-form E_n is proportional to the product of f_n and B_n, we may take it that, as a rule, E_n/E_1 is less than $1/n$. An exception to this may occur when the winding lies in an integral number of slots per pole and the corresponding value of B_n is very pronounced.

A further source of high-frequency harmonics is the effect of flux-swing resulting from the passage of stator and rotor teeth. Again we have harmonics of order $2Q \pm 1$. It should be noted that this number is not necessarily integral, as for example when there is not an integral number of slots per pole-pair. In this case the E.M.F. is periodic in the time of revolution of the shaft and not in the time of passage of the pole-pairs, and we should therefore take the former as our fundamental period to conform to the usual notation of harmonic analysis. Thus, what is usually known as the fundamental would be the 2nd, 3rd or higher harmonic, according to the number of pole-pairs.

When the dynamometer analyser is employed to determine the magnitude of the commutator ripples in rotary converters and d.c. machines, we have in general to measure an E.M.F. of single frequency.

Another application is in the analysis of current wave-forms such as the magnetizing current of transformers. No general indication can of course be given as to the probable order of magnitude of the harmonics in these cases. Numerous other applications will no doubt suggest themselves.

In the discussion of the errors of the method it is proposed to deal mainly with the first and most frequent case—the wave-forms likely to be given by commercial alternators. We shall discuss, therefore, the case in which only odd harmonics exist in the wave-shape and in which the ratio of the amplitude of harmonics of order n to that of the fundamental is less than $1/n$.

Let the imperfect analysing current used in the determination of the nth harmonic contain other harmonics than the nth. Let us suppose that

$$I_2 = i'_0 + I'_1 \sin(\omega t - \phi'_1) + I'_2 \sin(2\omega t - \phi'_2) + \ldots + I'_n \sin(n\omega t - \phi'_n) + \ldots + I'_x \sin(x\omega t - \phi'_x) + \ldots$$

and the current under analysis, i_1, is given by

$$i_1 = I_1 \sin(\omega t - \phi_1) + I_3 \sin(3\omega t - \phi_3) + \ldots + I_n \sin(n\omega t - \phi_n) + \ldots + I_x \sin(x\omega t - \phi_x) + \ldots$$

Then if d_1 be the actual reading of the dynamometer under these imperfect conditions, we find

$$d_1 = \tfrac{1}{2}k[I_1 I'_1 \cos\theta_1 + I_3 I'_3 \cos\theta_3 + \ldots I_n I'_n + \ldots + I_x I'_x \cos\theta_x + \ldots] \quad (3d)$$

where $\theta_1 = \phi_1 - \phi'_1$, etc.

If d be the reading which would be given, using a perfect analysing wave, then $d = \frac{1}{2}kI_nI'_n$.

The absolute magnitude of the error, δ, is therefore given by

$$\delta = \frac{2(d_1 - d)}{kI'_n}$$

and the magnitude of the error ψ relative to the magnitude of the fundamental is given by

$$\psi = \frac{2(d_1 - d)}{kI'_n I_1} = \frac{I'_1}{I'_n}\cos\theta_1 + \frac{I_3 I'_3}{I_1 I'_n}\cos\theta_3 + \ldots \frac{I'_{n-2} I_{n-2}}{I_1 I'_n}\cos\theta_{n-2} + \sum_{r=1}^{\infty} \frac{I_{n+2r} I'_{n+2r}}{I_1 I'_n}\cos\theta_{n+2r} \quad (3e)$$

The relative error ψ is thus represented by the sum of an infinite series whose terms depend, first, on the magnitudes of the ratios I_x/I_1, i.e. on the relative magnitudes of the harmonics in the wave under analysis, and, secondly, on the ratios I'_x/I'_n, i.e. on the freedom or otherwise of the analysing wave-form from impurities. It is essential, therefore, that these latter ratios should be small.

The convergency and limits of the series for ψ will be discussed later.

4. The Use of an Oscillatory Circuit to Obtain a Sinusoidal Analysing Current.

One of the first investigators to use the dynamometer method of analysis was Descoudres.* He obtained a sinusoidal E.M.F. of variable frequency by rotating a coil in the uniform field of a solenoid, the frequency being varied by driving the coil through gear wheels from a synchronous rotor. This apparatus was apparently quite satisfactory for harmonics up to the order of 9, but difficulties would probably arise in the extension of the method to harmonics of the order of 23, as a result of the high speed of rotation which would be necessary.

Dina † advocated the use of a multi-rotor alternator of the inductor type for generating the analysing current. The effect of the shape of the rotor and stator teeth on the wave-form would have to be closely studied before constructing such an alternator.

If the frequency of the wave under analysis were exactly constant, it would be a perfectly simple matter to generate a suitable analysing current by means of a triode oscillator. Unfortunately, however, in the majority of cases the variation in frequency of the supply under analysis would be sufficiently large to cause a periodic variation in the dynamometer deflection, as shown in (3c). Generally, as will be shown later, the frequency of this variation will be too high for any accurate results to be obtained. It is therefore necessary, in whatever method is adopted, to ensure that the frequency of the analysing wave is maintained at an exact multiple of the fundamental frequency of the wave under analysis.

The principal modification in the dynamometer method of analysis introduced in this paper consists in the application of the selective properties of an oscillatory circuit to obtain a sinusoidal current. We shall assume in the first place that it is possible to generate a complex wave-form of E.M.F.

$$e = \sum_{x=1}^{x=\infty} E_x \sin (x\omega t - \phi_x)$$

such that some harmonic of frequency $n\omega/(2\pi)$ has exactly the same frequency as one of the harmonics we wish to determine in a given wave-form.

We now proceed to consider the effect of applying this complex wave to the circuit represented in Fig. 1 when it is tuned to a frequency $n\omega/(2\pi)$.

The circuit consists of a choke coil, a high resistance and condenser in parallel, connected to the source of E.M.F. through a large non-inductive resistance.

Let L, r_1 = self-induction and resistance of choke coil.
C = capacity of condenser.
R_1 = non-inductive resistance of from 6 000 ohms to 50 000 ohms.
R = non-inductive resistance used as potential divider—200 000 ohms.

$$e = \sum_{n=1}^{n=\infty} E_n \sin n\omega t = \text{E.M.F. applied to AB.}$$

$$v = \sum_{n=1}^{n=\infty} V_n \sin (n\omega t - \phi_n) = \text{E.M.F. across DE.}$$

$$i = \sum_{n=1}^{n=\infty} I'_n \sin (n\omega t - \phi'_n) = \text{current in choke coil.}$$

We expect to find the current of frequency $n\omega$ in the choke coil predominant. We proceed to calculate,

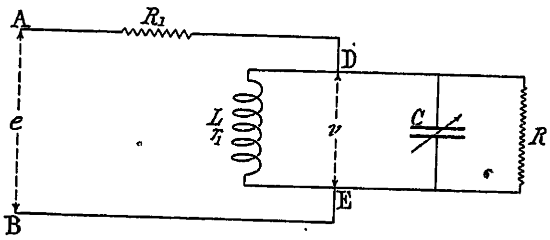

Fig. 1.—Diagram of circuit carrying a swinging current excited by voltage applied at AB.

first, the amplitude of the voltage V_n of frequency $n\omega$ across the terminals of the choke coil, and secondly the ratio of the amplitude of current of frequency $n\omega$ to that of any other frequency $x\omega$ in the choke coil, or I'_n/I'_x. It is evident that this ratio gives us the measure of the selective properties of the circuit.

It is shown in Appendix 1 that, with the above notation,

$$V_n = \frac{E_n}{1 + rR_1C/L} \quad . \quad . \quad . \quad . \quad (4)$$

where $\quad r = r_1 + \frac{1}{R} \cdot \frac{L}{C}$ (see Fig. 1)

and

$$\frac{I'_n}{I'_x} = \frac{E_n}{E_x} \cdot \frac{x^2 - n^2}{n} \cdot \frac{R_1\omega C}{1 + R_1rC/L} \text{ (approx.)} \quad . \quad (4a)$$

so that, as R_1 is increased to make R_1rC/L large compared with unity,

$$\frac{I'_n}{I'_x} = \frac{\omega L}{r} \cdot \frac{E_n}{E_x} \cdot \frac{x^2 - n^2}{n} \text{ (approx.)} \quad . \quad . \quad (4b)$$

To make the ratio I'_n/I'_x as large as possible and at the same time to keep V_n as large as possible, it is advisable to choose R_1 so that R_1Cr/L is of the order of three. It is also necessary to make the factor L/r

* *Elektrotechnische Zeitschrift*, 1900, vol. 21, pp. 752 and 900.
† *Elettrotecnica*, 1916, vol. 3, p. 3.

as large as possible. The limiting factor governing this ratio is the weight of copper required for the coil. We shall assume that it is possible to obtain a ratio L/r of the order of 1/15. If we now write

$$\frac{I'_n}{I'_x} = \lambda_{nx}\frac{E_n}{E_x}$$

we can tabulate values of λ_{nx} for a few typical values of n and x, assuming $\omega = 314$.

TABLE 1.

Values of λ_{nx} for Circuit 1.

n	x	λ_{nx}	n	x	λ_{nx}
1	3	128	5	1	77
	5	384		3	51
	11	1 920		7	77
	23	8 430		23	1 620
3	1	43	23	1	368
	5	85		5	351
	7	214		21	61
	23	2 800		25	67

It is therefore clear that even if all the harmonics in the applied wave were equal, the resulting current wave in the choke coil would possess very few harmonics greater than 1 per cent of the amplitude of the harmonic to which the circuit was tuned.

5. A Standard Method of Analysis in which the Analysing Current is Obtained from a D.C. Supply by the Use of a Multi-Part Commutator and Gear Wheels.

(*a*) The first method which was developed for producing the forced oscillations of the desired range of

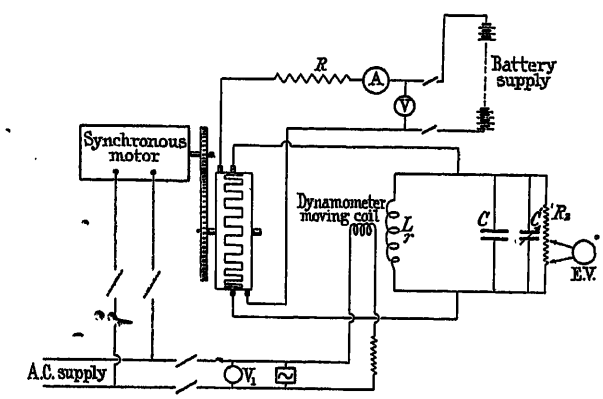

FIG. 2.—Commutator method of excitation.

frequencies, was to use a 46-part commutator driven at some fraction of the fundamental frequency by a synchronous motor and gear wheels. The outer rings of the commutator were connected to a d.c. supply, and the circuit in use was connected to the segments by a pair of brushes. The arrangement is illustrated diagrammatically in Fig. 2. The wave-form of the applied E.M.F. is then rectangular or trapezoidal in shape, as shown in Figs. 3 and 4.

If the frequency of the commutator is $[1/(2\pi)](n\omega/23)$, the frequency of the rectangular wave will be $n\omega/(2\pi)$. Each of these wave-shapes, as is well known, may be expressed as a Fourier series, and, if E_{dc} is the maximum

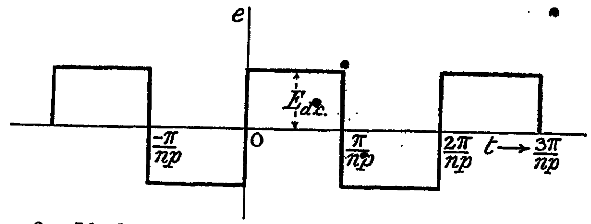

FIG. 3.—Ideal wave-shape of E.M.F. given by commutator.

value of the wave, we have for the rectangular shape of wave

$$e = \frac{4}{\pi}E_{dc}\left(\sin n\omega t + \frac{1}{3}\sin 3n\omega t + \ldots \frac{1}{x}\sin xn\omega t + \ldots\right) \quad . \quad (5)$$

and for the wave of trapezoidal shape

$$e = \frac{4}{\pi}E_{dc}\left(\frac{\sin\alpha}{\alpha}\sin n\omega t + \frac{1}{3}\cdot\frac{\sin 3\alpha}{3\alpha}\sin 3n\omega t + \ldots + \frac{1}{x}\cdot\frac{\sin x\alpha}{x\alpha}\sin xn\omega t + \ldots\right) \quad . \quad (5a)$$

Thus if $\omega = 314$ and $n = 1$, i.e. for a commutator speed of 3 000/23 r.p.m.,

$$e = \frac{4}{\pi}E_{dc}\left(\sin\omega t + \frac{1}{3}\sin 3\omega t + \ldots \frac{1}{x}\sin x\omega t + \ldots\right) \quad . \quad (5b)$$

whilst for $n = 3$, or a commutator speed of 9 000/23 r.p.m.,

$$e = \frac{4}{\pi}E_{dc}\left(\sin 3\omega t + \frac{1}{3}\sin 9\omega t + \ldots + \frac{1}{x}\sin 3x\omega t + \ldots\right) \quad . \quad (5c)$$

and for a commutator speed of 3 000 r.p.m.,

$$e = \frac{4}{\pi}E_{dc}\left(\sin 23\omega t + \frac{1}{3}\sin 69\omega t + \ldots + \frac{1}{x}\sin 23x\omega t - \ldots\right)$$

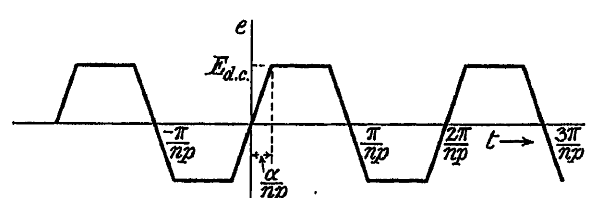

FIG. 4.—Possible wave-shape of E.M.F. given by commutator.

At first sight it might be thought that the gear wheels could be dispensed with altogether, simply using the impressed wave given by (5*b*) and tuning the circuit in turn to the various harmonics in it. It would be found, however, on calculating the magnitude of the fundamental component resulting in the analysing wave, that the error term, ψ, as found from (3*e*) would

be altogether too great. This results from the large magnitude of the ratio E_1/E_n in the impressed wave.

If, however, we change the commutator speed for each harmonic and tune the circuit to the fundamental of the rectangular wave in each case, we entirely eliminate the effect of the fundamental term in the wave under analysis. Thus if n be the order of the harmonic, the only harmonics in the auxiliary current will be those of order n, $3n$, $5n$, etc. In the determination of the 7th harmonic, for example, the error series will be given by

$$\psi = \frac{I_{21}}{I_1} \cdot \frac{I'_{21}}{I'_7} \cos \theta_{21} + \frac{I_{35}}{I_1} \cdot \frac{I'_{35}}{I'_7} \cos \theta_{35} + \ldots \quad (5d)$$

Thus, in addition to eliminating the effect of the fundamental, the number of important terms in the error series is reduced.

(*b*) *Forecast of errors.*—We have shown that the error is given by

$$\psi = \sum_{x=1}^{x=\infty} \frac{I_{xn} I'_{xn}}{I_1 I'_n} \cos \theta_{xn}$$

We may substitute from (4*a*), values of I'_{xn}/I'_n. Thus

$$\frac{I'_{xn}}{I'_n} = \frac{1}{\lambda_{nx}} \cdot \frac{E_{xn}}{E_n}$$

whilst from (5*a*),

$$\frac{E_{xn}}{E_n} \leq \frac{1}{x} \text{ (for odd values of } x)$$

and $E_{xn} = 0$ for even values of x.

It is shown in Appendix 2 that the resulting series for ψ is convergent for all values of n and that

$$\psi < \frac{1}{500} \times \text{max. value of } \frac{I_{xn}}{I_n} \quad . \quad . \quad . \quad (5e)$$

Thus, even if we had, in the wave under analysis, harmonics of the order (xn) having amplitudes equal to 25 per cent of the fundamental, we should still be in a position to measure any harmonic to within 0·05 per cent of the fundamental term.

We have already seen that this ratio of I_{xn}/I_n is never likely to be exceeded in any commercial alternator. Generally it will be less than $1/(xn)$; this will have a maximum value of $\frac{1}{9}$ for the case when $n = 3$ and $x = 3$, so that ψ will be less than 1/4 500.

We may therefore conclude that in the analysis of pressure waves of alternators by this method, the error introduced by the departure from the sinusoidal of the analysing wave will be negligibly small.

(*c*) *Details of apparatus.*—The complete diagram of apparatus used for the analysis is given in Fig. 2. The construction of the commutator does not require much description. It is built up from two brass castings with interlocking fingers, insulated from each other by mica. The castings are mounted on a steel shaft and insulated from this by a bakelite brush. The shaft is fitted with ball bearings and a U-shaped casting made to take these. The brushes are $\frac{1}{16}$ in. diameter hard-grade graphite pencils, and are held in small tubes attached to the brush rocker which fits over the bearing housings. The brushes can be displaced through any desired arc by a spring-and-screw adjustment.

The gear wheels were cut to a diametrical pitch of 48 to 1 in., the pitch diameters varying from $\frac{3}{4}$ in. to $5\frac{3}{4}$ in.

A ring-wound two-pole d.c. motor was adapted for use as a synchronous motor, and gave satisfactory service apart from a tendency to phase-swing. The motor and commutator were mounted on a bedplate, slotted to allow of adjustment for the various gear wheels.

The main considerations governing the design of the oscillatory circuit were:—

(i) The ratio of effective resistance to self-induction, r/L, had not to be much greater than 15.
(ii) The circuit had to be capable of oscillating at all frequencies from 30 to 1 100 cycles per second.

The choke coil was therefore designed to satisfy the following conditions:—

(i) To have a minimum self-induction of the order of 0·004 henry and to enable simple multiples of this to be obtained.
(ii) To have a ratio of resistance to self-induction, when measured with direct current, of the order of 10.
(iii) To have as low as possible a ratio of effective resistance at a frequency of 1 100 to resistance measured with direct current.

Details of the calculation for a similar coil constructed later are given in Appendix 3. To obtain the required ratio of r/L, about 170 lb. weight of copper was used, whilst to keep the eddy-current loss at high frequencies low, the coil was wound with 0·018 in. wire. The variation in self-induction was obtained by a series—parallel grouping of the layers, each layer being brought out to separate terminals. To obtain a low figure for the minimum self-induction with all the layers connected in parallel, it was necessary to wind four strands in parallel. The exact number of turns per layer was calculated, so that the mutual inductance between any one layer and the remainder of the coil was the same for all the layers, thus ensuring approximately equal distribution of current at all frequencies. It was further found that to obtain the maximum value of L/r for a given weight of copper, the section of the coil had to be rectangular and not square as in the case of direct current.

It is shown later that the dimensions of the coil might have been much reduced by the use of a valve as a negative resistance.

The large capacity C in the oscillatory circuit was subdivided into steps of 40, 20, 20, 10, 5, and 5 μF, giving a total of 100 μF, and was suitable for continuous working at 100 volts. The small tuning condenser C′ covered a range from 0·1 to 8·0 μF in convenient steps.

It is essential that the condensers used shall have a small dielectric loss. The effect of this loss on the effective ratio r/L for the circuit is easily found. Thus

when the power factor of the condensers is small we have

$$\cos\phi = r_c\omega C \text{ (approx.)}$$

where r_c is the effective resistance of the condensers. Also, for resonance

$$\omega C = 1/(\omega L) \text{ (approx.)}$$

so that

$$r_c/L = \omega \cos\phi$$

The power factor of good paper condensers does not vary much with frequency and in the range of frequencies from 50 to 2 000 and for the large capacity condensers used was of the order of 0·0025. Their contribution to the effective r/L of the circuit was therefore of the order of 20 at a frequency of 1 100. To reduce this addition to the loss still further, it would be necessary to use mica condensers. These, however, were not available at the time, and so the effective resistance at the higher frequencies was larger than had been desired.

To show the necessity for care in this matter, the power factor of one set of condensers in use in the laboratory proved to be of the order of 0·03. The use of these in the oscillatory circuit would have resulted in an addition to the effective ratio r/L of about 200 at the higher frequencies.

Design of instruments.—It has been shown previously that the calculation of the amplitude of a harmonic is made from the readings of the dynamometer and of the instrument measuring the analysing current. A good way of measuring this current is to measure the voltage across the terminals of the choke coil.

It was essential in the first place that the instrument used should not increase the effective resistance of the circuit to any great extent, and its power consumption had therefore to be small. The most suitable instrument available in the laboratory for the measurement of the analysing current was a reflecting-type electrostatic voltmeter, giving full-scale deflection for 10 volts. This was used in conjunction with a 200 000-ohm-resistance potential divider to measure the E.M.F. across the oscillatory circuit. The frequency and self-induction of the choke coil being known, the current in the choke coil can be calculated from the formula $I_n' = V_n/(n\omega L)$, since the error caused by neglecting the effect of the resistance of the coil can easily be shown to be negligible for the given r/L of the coil. It has since been shown that the Moullin thermionic voltmeter possesses satisfactory properties for the purpose.

To eliminate the losses which would have been inevitable in the use of a separate dynamometer instrument, the choke-coil was so designed that it could be used as the fixed coil of the dynamometer. A moving coil with a bifilar suspension was placed inside the fixed coil, the magnetic axes of the two coils being at right angles. As the flux density at the middle of the large coil could not be large, the deflection of the moving coil is small and necessitates the use of an optical system for the measurement of the deflection. Thus, a concave mirror of 2 m radius was fixed to the moving coil and the reflection of an illuminated scale observed by means of a telescope immediately above the latter, the scale and telescope being 3·3 m. from the moving coil. The moving coil was constructed to have a small radius of gyration, the natural period being about 0·5 second. It was wound on a former 21 × 1·1 × 0·4 cm, using 200 turns of 0·0076 in. wire. The bifilar suspension was 5 cm long, spaced 0·7 cm. To make the movement dead-beat, an oil-immersed paddle was attached. A non-inductive resistance of 1 000 ohms was included in the moving-coil circuit so that it could be used on a 100-volt circuit.

A sketch of the moving coil of the dynamometer system is given in Fig. 5, and details of the movement in Appendix 3.

Sensitivity.—It is clear that the sensitivity obtainable depends on the number of ampere-turns it is possible to have in the fixed coil. This in turn is limited by the voltage it is possible to obtain across the resonating circuit. The rating of the condensers and the limiting potential difference it is possible to use between adjacent commutator segments fix this at a maximum of about 100 volts (R.M.S.)

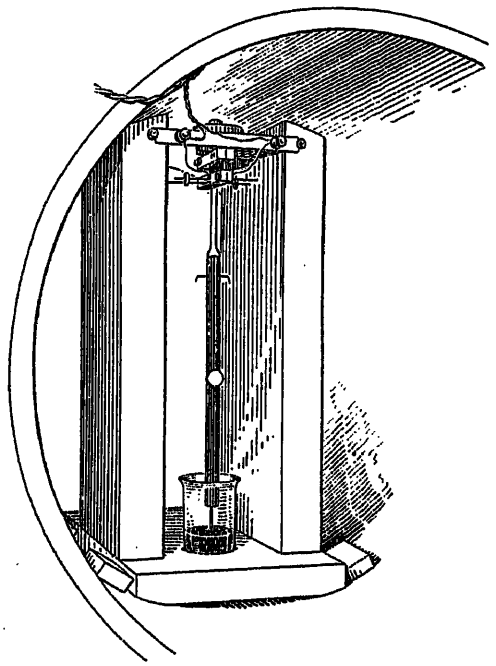

FIG. 5.—Sketch of dynamometer moving-coil.

If now T be the number of turns in series in the coil, and L the self-induction, we have $L = bT^2$, where b is a constant, so that

$$\text{Ampere-turns} = \frac{E}{\omega L}T = \frac{E}{b\omega T}$$

Thus for a maximum number of ampere-turns we require the minimum self-induction and the maximum capacity for any frequency. The factor limiting the possible capacity is the weight and portability of the condensers used, so that 100 μF may be taken to be a maximum. At the higher frequencies the limiting factor is the minimum self-induction it is possible to obtain with all the layers of the coil in parallel. This was reduced

as far as possible by winding the coil with four strands in parallel, giving a minimum self-induction of 0·0036 henry.

At a frequency of 1 150 it was therefore possible to obtain 400 ampere-turns in the fixed coil, giving an R.M.S. flux density at the centre of the coil of the order of 12 C.G.S. units. With the moving coil constructed, an E.M.F. of 1 volt across the terminals of the moving-coil circuit would give a torque of about 6 dyne-cm on the coil, resulting in a deflection of 0·1°, or 1 cm on the scale.

Since we can certainly read the scale to 0·05 cm, the value of a harmonic should be determinable to within 0·05 per cent of the fundamental. The sensitivity could, if necessary, be still further increased at the expense of the time period of the moving coil, by reducing the controlling torque.

Calibration.—The dynamometer was calibrated with direct current, care being taken to correct for the earth's field.

If e_n be the R.M.S. value of the harmonic under determination, Z_n the impedance of the moving-coil circuit to this harmonic, N the number of ampere-turns in the fixed coil and d the deflection of the dynamometer when the phase of the analysing current is adjusted to give a maximum, then

$$d = D\frac{e_n}{Z_n}N \quad . \quad . \quad . \quad . \quad . \quad . \quad (5f)$$

where D is the dynamometer constant.

Possible sources of error.—The sources of error in the methods of measurement adopted above are as follows :—

(i) The electrostatic voltmeter deflection is proportional to the sum of the square of the amplitudes of all the harmonics present in the voltage across the oscillatory circuit, and not simply to the square of the amplitude of the harmonic under determination.

(ii) The impedance of the moving-coil circuit is not quite independent of frequency, the self-induction being of the order of 6 mH. At a frequency of 1 150 the error introduced by this will only be of the order of 0·1 per cent.

(iii) The mutual induction between the fixed and the moving coils of the dynamometer causes an error proportionate to the square of the frequency and so may be important for the higher harmonics.

(iv) The distribution of current in the fixed coil may change slightly with frequency and so affect the constants of the instrument.

These sources of error are considered in Appendix 4, and are there shown to be negligible.

(*d*) *Method followed in the analysis of a voltage wave-form.*—The diagram of connections is given in Fig. 2. The brush gear on the commutator is first adjusted so that the inner brushes are in exactly corresponding positions on oppositely connected segments of the commutator. The outer brushes are connected to a battery supply giving up to 250 volts, a non-inductive resistance of the order of 50 000 ohms being connected between the battery and commutator. The gear wheels necessary for the particular harmonic under measurement are fitted and the motor run up to speed and synchronized with the machine or supply whose wave-form is to be analysed.

The value of capacity required in the resonating circuit is calculated, the layers of the choke coil being connected to give the largest possible value of capacity for the given frequency. The supply switch to the commutator is closed, and the oscillatory circuit tuned to give approximately a maximum reading on the electrostatic voltmeter.

The moving-coil circuit is closed and the brush rocker on the commutator moved until a maximum reading is obtained on the dynamometer scale. Before taking a final reading, the tuning of the oscillatory circuit is adjusted to the exact resonance point. The R.M.S. voltage of the supply under test is read by an ordinary precision voltmeter, and the frequency determined either by a frequency meter or a tachometer. The ampere-turns of the fixed coil are calculated from the reading of the electrostatic voltmeter, and the amplitude of the harmonics are then determined from (5*f*). Thus we have:

$$E_n = \frac{1}{D} \cdot \frac{Z_n}{N}$$

The greatest source of trouble in this method is the effect of sparking at the commutator segments, the carbon deposited from the brushes causing partial short-circuits as a result of the high potential difference existing between segments. The difficulty was partly overcome by making small sleeves of copper gauze to slip over the tips of the pencils, but this could not be regarded as a satisfactory permanent arrangement.

Phase-swinging of the synchronous motor was a further source of trouble. It results in a periodic variation in θ_n, the angle of phase difference between the analysing current flux and harmonic current. The variation is of course worse for the higher harmonics, since a change of 1° in θ, the phase difference for the fundamental, means a change of 23° in θ for the 23rd harmonic. Since the deflection of the dynamometer is proportional to cos θ_n, the amplitude of the variation for small values of θ_n is proportional to sin θ_n and is small when θ_n is small. Thus when the brushes were adjusted to give a maximum reading on the dynamometer scale, the variation became small and it was in all cases possible to obtain readings with an accuracy of 1 to 2 per cent of the full deflection. It would no doubt be possible to reduce this source of trouble very considerably by using a properly designed motor. The motor used had solid poles, but no dampers.

(*e*) *Tests on completed apparatus.*—The tests carried out on the completed apparatus were as follows :—

(i) Oscillographic investigation of current and voltage wave-forms in various parts of the circuit.

(ii) Analysis of oscillograms of analysing current wave.

(iii) Analysis of open-circuit pressure wave of Kolben three-phase alternator, and comparison of results with analysis of oscillograms recording the same waves.

(iv) Experimental proof of the accuracy of the method.

During the course of the tests it was found that the effective ratio r/L of the circuit increased from the d.c. value of 10 to a limiting value of the order of 50 for the higher harmonics. This was probably due in part to defective insulation in the large coil. The tests were proceeded with, but it is to be expected, from the theoretical discussion given above, that the errors obtaining will be of a higher order than would have been obtained had the ratio r/L been 15, as anticipated.

Test (*i*).—Fig. 7 shows the E.M.F. wave given by the commutator when running at a frequency of 50. The oscillograph used was the Duddell type having a natural frequency of 3 000.

Fig. 8, curve A, shows the wave-form of the current flowing into the condenser of the oscillatory circuit.

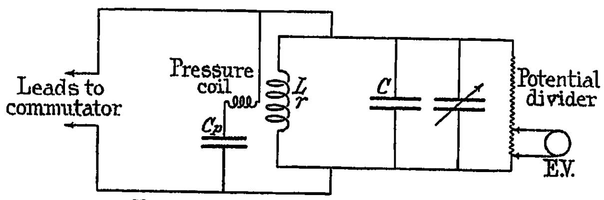

FIG. 6.—Connections for test (iv).

C_p = small-capacity condenser (0·1 μF)
E.V. = electrostatic voltmeter.

The ripples show the points where the condenser receives energy from the commutator. Curve B is the wave-form of the analysing current in the choke coil.

Fig. 9 records the rate of change of the current in the choke coil. It was obtained by connecting a small search coil to the oscillograph elements and approaching this coil to the choke coil until a sufficient deflection was obtained on the oscillograph. By this means any harmonics in the analysing wave will be magnified in proportion to their order. It will be seen that it is remarkably free from higher harmonics.

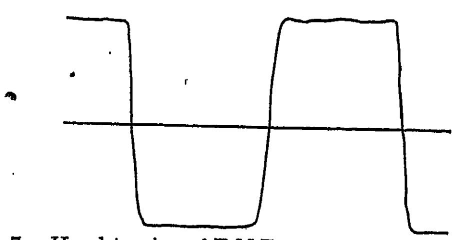

FIG. 7.—Hand tracing of E.M.F. wave-form from commutator.

Test (*ii*) : *Analysis of Fig.* 9.—Fig. 9 was analysed by the Runge method, using 14 ordinates per half-cycle. No harmonic greater than 0·1 per cent of the fundamental was found to exist in the actual current wave.

Test (*iii*) : *Analysis of phase and line voltage of* 30-*kW Kolben alternator for fixed load and excitation.*—This machine forms part of the equipment of the electrical laboratories of the Manchester College of Technology. It has 6 slots per pole in the armature and might therefore be expected to have predominant 11th and 13th harmonics. The only load on the machine during the test was due to the synchronous motor, and since this was of the order of 0·4 kW it would have very little effect on the wave-form.

The phase-voltage and line-voltage waves were analysed by the dynamometer, and oscillograms of the same waves were taken by two separate oscillographs. Both oscillographs were of the Duddell type, having natural frequencies of 3 000 and 7 000 respectively. The oscillograms were analysed by Clayton's modification of the Runge method, using 26 ordinates per half-cycle. The results are given in Table 2.

The probable order of accuracy of the results for the dynamometer method is indicated in each case, the figures being based on the steadiness and consistency of the readings obtained. It will be noted that for the most part they lie within the limits $\pm$ 0·1 per cent of the fundamental. The oscillograms were not enlarged for analysis, and greater accuracy than to within 1 per cent of the fundamental could hardly be hoped for.

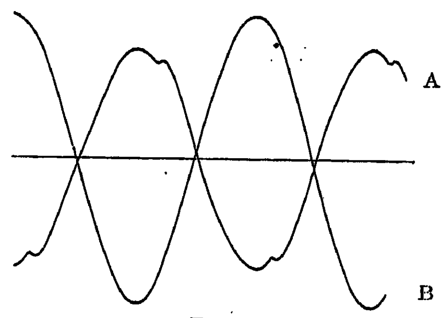

FIG. 8.

Curve A, current in condenser of oscillatory circuit.
Curve B, current in choke coil.

It will be noted, on comparing the figures for the harmonics in the phase and line pressures respectively, that the 3rd and 9th harmonics do not quite disappear in the line pressure. This is probably due to lack of balance in the phases.

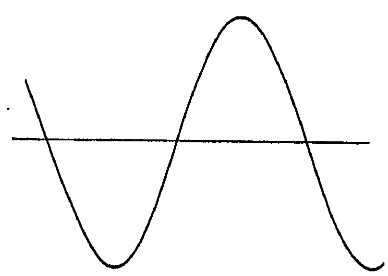

FIG. 9.—Rate of change of current in choke coil.

The 15th and 21st harmonics were not determined, as gear wheels corresponding to these orders had not been cut.

Figs. 10 and 11 show the oscillograms of the two wave-forms analysed.

Test (*iv*) : *Experimental proof of the accuracy of the method.*—If we can prove:—

(i) That the reading obtained on the dynamometer for any harmonic is independent of the values of all the other harmonics; and

(ii) That the method gives a correct value for the amplitude of an E.M.F. wave of any single frequency,

it follows that the reading obtained for any harmonic of a complex wave is correct.

To prove (i), let us suppose that the reading obtained for the nth harmonic *is* affected by the other harmonics.

TABLE 2.

Analysis of Phase and Line Voltage of Three-Phase Kolben Alternator at 45 Cycles per sec.

	Line voltage, per cent			Phase voltage, per cent		
Order of harmonic	By dynamometer	By low-frequency oscillograph	By high-frequency oscillograph	By dynamometer	By low-frequency oscillograph	By high-frequency oscillograph
	per cent	per cent	per cent	per cent	per cent	per cent
1	100	100	100	100	100	100
3	0·53 ± 0·01	0·0	0·6	10·0 ± 0·05	11	11
5	5·7 ± 0·1	5·6	5·6	6·0 ± 0·20	4·3	4·1
7	0·20 ± 0·03	1·8	0·6	0·24 ± 0·03	1·4	0·5
9	0·04 ± 0·01	0·0	0·3	7·5 ± 0·1	5·6	8·3
11	—	3·3	1·6	2·7 ± 0·05	0·4	2·3
13	5·2 ± 0·1	5·2	5·2	5·1 ± 0·1	2·9	4·5
15	—	—	—	—	—	—
17	0·66 ± 0·03	0·9	0·8	0·62 ± 0·03	0·5	0·6
19	0·63 ± 0·03	0·4	0·5	—	—	—
21	—	—	—	—	—	—
23	2·4 ± 0·1	1·2	2·0	2·4 ± 0·1	0·4	2·2

We have

$$d_n = \mu_n E_n + \mu_1 E_1 + \mu_3 E_3 + \ldots + \mu_x E_x + \ldots$$

where $E_1, E_3 \ldots E_n$ are the amplitudes of the various

FIG. 10.—Line voltage of Kolben alternator.

harmonics of E.M.F. applied to the moving-coil circuit of the dynamometer, and $\mu_1, \mu_3, \mu_5 \ldots \mu_n$ are constants

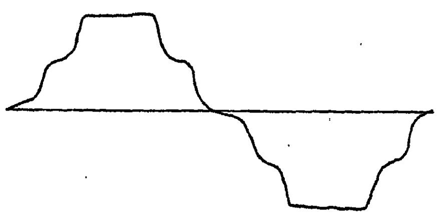

FIG. 11.—Phase voltage of Kolben alternator.

for fixed conditions of the oscillatory circuit and fixed impedance of the moving-coil circuit.

Suppose now that we substitute a small-capacity series condenser for the series resistance of the moving-coil circuit, so that the impedance of the circuit becomes approximately $1/(n\omega C_p)$ to the nth harmonic (see Fig. 6); and suppose then the phase of the analysing current was readjusted to give a maximum reading of the dynamometer, the amplitude of the current being maintained constant.

Then let d_n' be the new deflection obtained; for μ_x we must write $\mu_x r x\omega C\lambda_x$ and for μ_n, $\mu_n rn\omega C$, the factor λ_x being necessary since the phase relations between flux and current of frequency $x\omega$ are no longer the same.

Thus we have

$$d_n' = r\omega C(n\mu_n E_n + \mu_1 E_1\lambda_1 + 3\mu_3 E_3\lambda_3 + \ldots + x\mu_x E_x\lambda_x)$$

and

$$\frac{1}{rn\omega C}\cdot\frac{d_n'}{d_n} = \frac{E_n + \frac{1}{n}\cdot\frac{\mu_1}{\mu_n}\lambda_1 E_1 + \frac{3}{n}\cdot\frac{\mu_3}{\mu_n}\lambda_3 E_3 + \ldots\frac{x}{n}\cdot\frac{\mu_x}{\mu_n}\lambda_x E_x}{E_n + \frac{\mu_1}{\mu_n}E_1 + \frac{\mu_3}{\mu_n}E_3 + \ldots\frac{\mu_x}{\mu_n}E_x} \quad (5g)$$

If now we can find experimentally $\frac{1}{rn\omega C}\cdot\frac{d_n'}{d_n}$ for various values of n and show it to be equal to unity in all cases, within the limits of experimental error, then the only reasonable conclusion is that

$$\mu_1 = \mu_3 = \mu_5 = \ldots \mu_x = 0 \neq \mu_n$$

In other words, the reading obtained for any one harmonic is independent of the values of all the other harmonics.

In carrying out this test it should be noted that when using a series condenser in the moving-coil circuit the error due to the mutual induction between fixed and moving coils of the dynamometer is greatly increased, since the induced current in the moving coil is brought

into phase with the inducing flux. The magnitude of the error has therefore to be found at all positions on the scale and for all frequencies, and the correction applied.

The results obtained are given in Table 3.

TABLE 3.

Order of harmonic, n	d_n	$\frac{1}{rn\omega C}d'_n$
3	10·0 ± 0·05	10·1
5	6·0 ± 0·2	5·8
7	0·24 ± 0·03	0·20
9	7·5 ± 0·10	7·6
11	2·7 ± 0·05	2·7
17	0·62 ± 0·03	0·63

Within the limits of experimental error $\frac{1}{rn\omega C}\cdot\frac{d'_n}{d_n}$ is equal to unity and we may therefore take it that to a sufficient degree of approximation the reading obtained on the dynamometer for one harmonic is independent of the values of all the other harmonics.

To prove (ii), the amplitude of the E.M.F. across the oscillatory circuit when tuned to the 19th harmonic was measured by the dynamometer and the result compared with the value given by a direct reading on the electrostatic voltmeter. The connections for this test are given in Fig. 6.

It is necessary to replace the series resistance in the moving-coil circuit of the dynamometer by a small-capacity series condenser in order to bring the moving-coil current into phase with the fixed-coil flux.

It was shown that with a deflection of 90 cm on the scale the current as calculated from the dynamometer reading and that calculated from the reading of the electrostatic voltmeter agreed to within ± 1 per cent. This would in general be within 0·1 per cent of the fundamental.

We have therefore proved that this dynamometer method will give values for the harmonics of a complex wave correct within the limits ± 0·1 per cent, provided the dynamometer and electrostatic voltmeter can be read to this degree of accuracy. Generally the limiting factor in the accuracy attainable is the unsteadiness of the deflections obtained.

(*f*) *Conclusions.*—The method of analysis outlined above is one which allows a much higher degree of accuracy to be obtained in the determination of harmonics of orders up to 30 than has been possible previously. Results should in general be accurate to within 0·1 per cent of the fundamental, whilst harmonics of amplitudes less than 1 per cent of the fundamental may be measured to within 0·05 per cent of the fundamental.

The figures obtained in the tests given above would undoubtedly have been improved upon had the effective ratio r/L for the oscillatory circuit been of the order of 15 instead of 50. The apparatus with the commutator is, however, too complicated for general commercial use and its principal value will probably be to act as a standard against which other methods may be checked as they are developed.

The authors therefore proceeded to design a simpler apparatus.

6. A METHOD OF ANALYSIS IN WHICH THE ANALYSING CURRENT IS OBTAINED FROM THE A.C. SUPPLY BEING ANALYSED.

(*a*) *General principles of method.*—In Section 5 it was shown that, by using the dynamometer principle and obtaining the necessary sinusoidal analysing current by tuning an oscillatory circuit to the fundamental of a rectangular E.M.F. wave of suitable frequency, a method is obtained which possesses very considerable accuracy and which may therefore be termed a standard method. The rectangular E.M.F. wave for this method must have the frequency of the harmonic being found, and is obtained from a d.c. supply by means of a multi-part commutator driven at an appropriate speed, which will of course be different for the different harmonics.

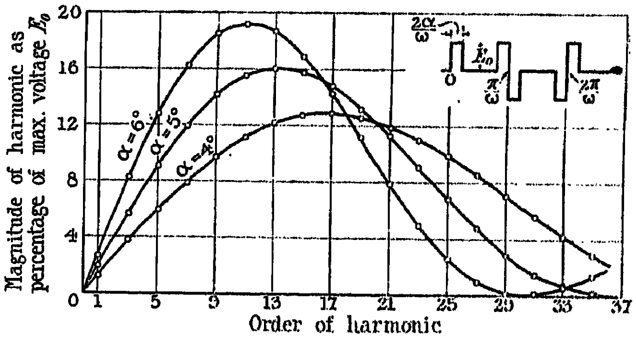

FIG. 12.—Curves showing the magnitudes of the various harmonics in the given wave-form for several values of α.

The method of analysis now to be described was developed from this standard method by two important modifications. In the first place, to avoid the necessity of inducing in the oscillatory circuit an E.M.F. wave of a different frequency for each harmonic to be found, the oscillatory circuit was tuned to the various harmonics in a single E.M.F. wave of a suitable form. In the second place, to avoid introducing the inherent drawbacks of a commutator and the need for a separate d.c. supply of energy, this special E.M.F. wave was obtained from the a.c. supply being analysed, by the use of a saturated transformer and neon-filled glow-lamps.

Since the fundamental frequency of the induced E.M.F. wave will be that of the wave being analysed, the series for the dynamometer error will have terms corresponding to each harmonic in the wave under analysis. In this series the term due to the presence in the analysing current of a harmonic of fundamental frequency will in general be by far the most important, and so from general considerations an E.M.F. wave is required in which the fundamental is small compared with the lower harmonics.

As it is difficult to obtain a practical wave-form with

no fundamental, the most convenient wave for our purpose is one in which the magnitudes of the lower harmonics are approximately proportional to their orders. The simplest of such wave-forms is that shown in Fig. 12, which contains only odd harmonics and no cosine terms.

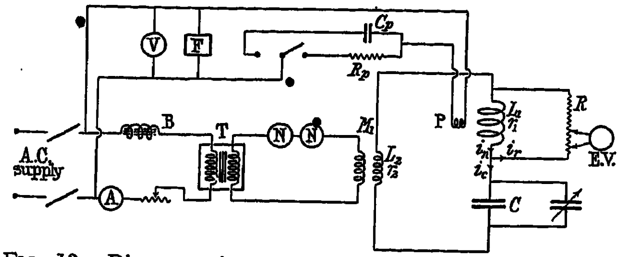

FIG. 13.—Diagram of connections for neon-lamp method of analysis.

B = adjustable choke coil.
T = saturated transformer.
N = neon-filled glow-lamp.
M_1 = air-core mutual inductance.
P = pressure coil of dynamometer.
C_p = small-capacity condenser (0·1 μF).
R_p = non-inductive resistance (1 000 ohms).
F = frequency meter.
E.V. = electrostatic voltmeter.

By the usual process for determining the Fourier coefficients of a periodic wave, we have

$$A_n = \text{amplitude of } n\text{th harmonic} = \frac{\omega}{\pi}\int_0^{2\pi/\omega} f(t) \sin n\omega t\, dt$$

$$= \frac{8E_0}{\pi} \cdot \frac{\sin^2 n\alpha}{n}$$

where $f(t)$ gives the form of the E.M.F. wave;

E_0 = max. value of E.M.F.; and
$\alpha = \frac{1}{4}$ phase angle of duration of each complete impulse of E.M.F.

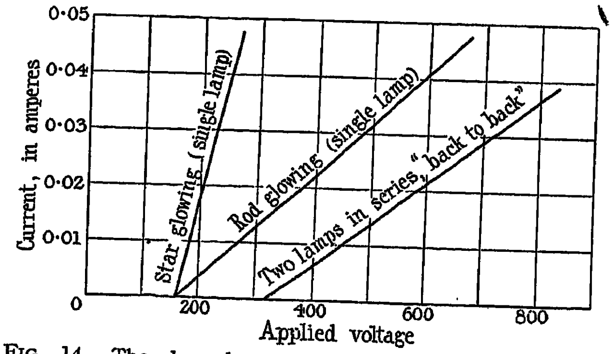

FIG. 14.—The d.c. characteristic of an "Osglim" neon-filled lamp, neglecting a small hysteresis effect.

The amplitudes of the various harmonics in this wave-form for several values of α are shown in Fig. 12. The method of obtaining the analysing current from the a.c. supply being analysed will now be dealt with; it has for its object the induction in the oscillatory circuit of an E.M.F. wave approximating to the one just considered.

(*b*) *A method of inducing a suitable E.M.F. wave in the oscillatory circuit by the use of a saturated transformer and neon-filled glow-lamps.*—The desired E.M.F. wave may be induced in the oscillatory circuit by means of the circuit shown in Fig. 13. The primary of a saturated transformer is connected to the a.c. supply to be analysed through a choke coil such that the current is maintained almost sinusoidal, and saturation takes place early in each half-cycle.

The wave-form of E.M.F. given by the secondary of the transformer is as shown in Fig. 15(*a*).

The secondary circuit of the transformer is completed through several neon-filled glow-lamps, and the primary of an air-core coupling with the oscillatory circuit.

The characteristic of the neon lamp enables us to utilize only the sharp peaks of the secondary E.M.F. wave from the transformer, and thereby to keep to a minimum the magnitude of the fundamental in the resultant current wave.

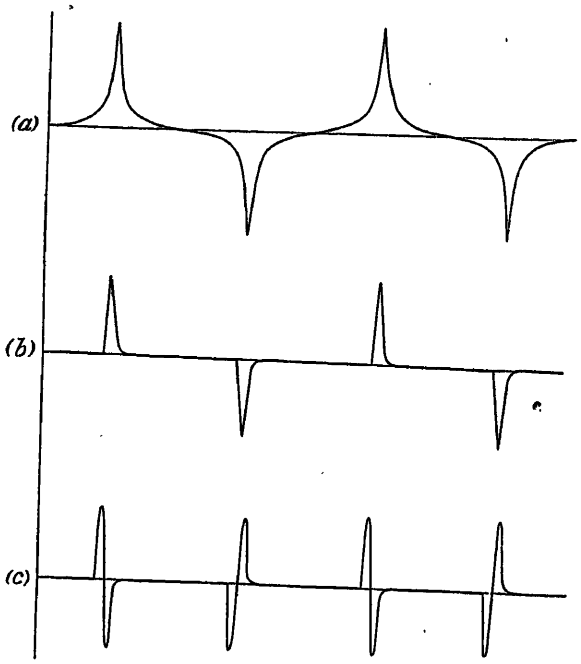

FIG. 15.—Reproductions from oscillogram records taken with Duddell high-frequency oscillograph.

(*a*) Secondary voltage of saturated transformer.
(*b*) Neon-lamp current.
(*c*) E.M.F. induced in oscillatory circuit.

The d.c. characteristic of the neon lamp is such that a definite E.M.F. e is required to start the current in either direction. For an applied E.M.F. less than e there is no current, while for a greater E.M.F. the lamp behaves as a large non-inductive resistance where the effective E.M.F. is equal to the applied E.M.F. minus the starting E.M.F. e. This gives practically a straight-line characteristic, neglecting a small hysteresis effect.

In the actual lamps manufactured, owing to dissimilar electrodes the effective resistance is different for the two directions of current. However, by always using these lamps in pairs, with those of each pair "back to back," a single characteristic can be obtained as shown in Fig. 14. If it is required to make α (see Fig. 12) small, it may be necessary to use four neon lamps in series.

The starting E.M.F. is about 160 volts for each lamp, so that the maximum E.M.F. given by the transformer

may have to exceed 1 500 volts if four neon lamps are used in series.

A current having an almost triangular wave-form over a small part only of each half-cycle, as shown in Fig. 15 (*b*), is obtained in the neon-lamp circuit. This current induces an E.M.F. approximating to the desired wave-form [Fig. 15 (*c*)] in the oscillatory circuit.

(*c*) ***The harmonics in the E.M.F. wave induced in the oscillatory circuit.***—The wave-form of E.M.F. induced in the oscillatory circuit is similar to the theoretical wave already considered, except that the corners are considerably rounded off. It is to be expected from this that the higher harmonics will be smaller and will fall off more rapidly than in this theoretical wave.

(ii) By the analysis of an oscillogram record of the given E.M.F. wave obtained with the Duddell high-frequency oscillograph, by the Clayton modification of the Runge method, using selected ordinates.

The magnitudes of the harmonics found by these two methods are shown in Fig. 16. A reproduction of the oscillogram of this E.M.F. wave is also given. The harmonics in the limiting forms, rectangular and triangular, of the E.M.F. wave shown in Fig. 17 are also indicated by the dotted curves for comparison purposes.

It can easily be shown by the ordinary process for determining the Fourier coefficients of a wave-form,

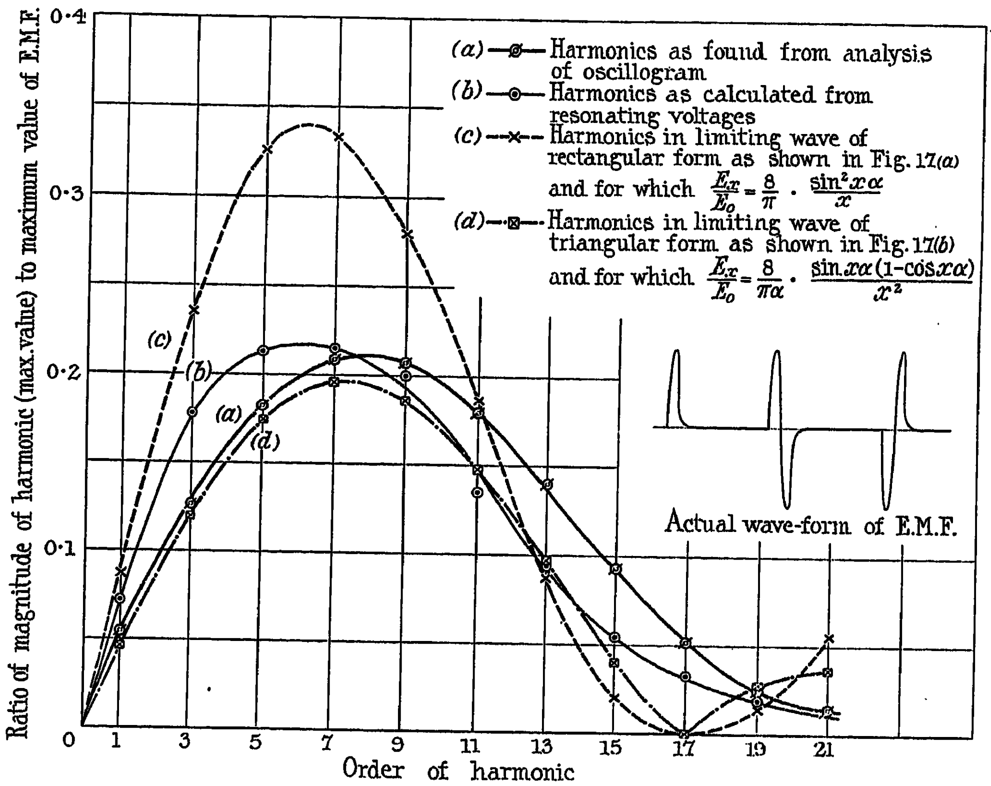

FIG. 16.—The harmonics in the E.M.F. wave induced in the oscillatory circuit.
NOTE :—Only odd harmonics in the wave-forms represented.

From the symmetry of the wave we can predict that no even harmonics will be present, and that the cosine terms will be negligibly small compared with the sine terms if time is measured from the instant of zero E.M.F. at the middle of the double impulse.

The actual harmonics in the E.M.F. wave obtained, for a given setting of the transformer primary and secondary circuits, were calculated :

(i) From the magnitudes of the resonating voltages across the main coil, with the circuit tuned in turn to the various harmonics in the E.M.F. wave, by the use of the formula

$$E_n = V_n\left(\frac{r_1 + r_2}{n\omega L_1} + \frac{n\omega L_1}{R}\right)^*$$

* See Appendix 6, Equation (31).

that for the rectangular wave [Fig. 17 (*a*)] the *x*th harmonic, where *x* is odd, is

$$A_x = \frac{8E_0}{\pi} \cdot \frac{\sin^2 x\alpha}{x}$$

and for the triangular wave [Fig. 17 (*b*)] the *x*th harmonic is

$$B_x = \frac{8E_0}{\pi\alpha} \cdot \frac{\sin x\alpha(1 - \cos x\alpha)}{x^2}$$

All the even harmonics are zero for both these wave-forms.

Curves (*c*) and (*d*) in Fig. 16 were plotted from these expressions, the value of α taken being the mean value found from the oscillogram record, which in this case was 0·185 radian = 10·6°.

It is seen that for $x < 11$, i.e. for $x\alpha < 110°$, the actual harmonics in the E.M.F. wave are intermediate between the corresponding harmonics in the two limiting wave-forms. The actual harmonics are, however, so much nearer to those in the triangular than to those in the rectangular form of the limiting wave, that the former may be taken as quite a fair approximation to the actual wave up to $x\alpha = 140°$.

To measure harmonics up to the 23rd, the supply to the oscillatory circuit must be so adjusted that the value of α for the induced E.M.F. is about 6°, this giving a wave-form in which the maximum harmonic is in the neighbourhood of the 11th or 13th, and the first negligibly small harmonic near the 29th or 31st. The graphs could not be given for this case as experimental figures were not available.

(*d*) *The harmonics in the analysing current of the dynamometer and the theoretical error due to them.*—The oscillatory current will be the analysing current that passes through one coil of the dynamometer, whether the main inductance be used as the fixed coil of the dynamometer or whether the latter be an entirely separate instrument.

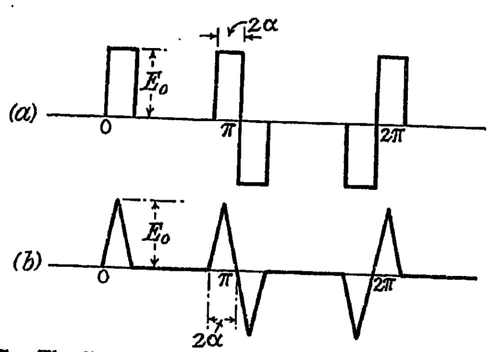

FIG. 17.—The limiting forms of the E.M.F. wave induced in the oscillatory circuit.

Let n = order of harmonic being found, which is also the order of the harmonic in the E.M.F. wave to which the oscillatory circuit is tuned.

x = order of any other harmonic.

E_n, I'_n = nth harmonics (maximum values) of induced E.M.F. and resultant current respectively, in oscillatory circuit.

E_x, I'_x = harmonics of E.M.F. and current of order x.

For the given oscillatory circuit we have, from Equation (29) Appendix 6,

$$\frac{I'_n}{I'_x} = \frac{E_n}{E_x} \cdot \frac{\omega L}{r} \cdot \frac{x^2 - n^2}{x} \text{ (to a 1st approximation)}$$

where L = total inductance in oscillatory circuit $= L_l + L_2$
and r = total effective resistance of oscillatory circuit $= r_1 + r_2 + n^2\omega^2 L_1^2/R$

As it is impossible to make an exact calculation of the error, the above approximation for I'_n/I'_x will suffice for our purpose.

It has already been shown [see 3(*e*)] that for the dynamometer the error due to the analysing current not being sinusoidal is given in terms of the fundamental by

$$\psi = \sum_{x=1}^{x=\infty} \frac{I_x}{I_1} \cdot \frac{I'_x}{I'_n} \cos \theta_x$$

(noting that, by definition, x cannot equal n).

An upper limit is found to the maximum possible value of this series by replacing $\cos \theta_x$ by unity in each term, substituting for I'_x/I'_n, and then summing the series in two sections corresponding to ranges of x from 1 to x_0 and from $(x_0 + 2)$ to ∞, where x_0 is chosen greater than the highest value of n required.

$$\frac{I'_x}{I'_n} = \frac{E_x}{E_n} \cdot \frac{r}{\omega L} \cdot \frac{x}{x^2 - n^2} \text{ approx.}$$

from Equation (29), Appendix 6, and so

$$\psi \leqslant \frac{r}{\omega L} \sum_{x=1}^{x=x_0} \frac{I_x}{I_1} \cdot \frac{E_x}{E_n} \cdot \frac{x}{x^2 - n^2} + \frac{r}{\omega L} \sum_{x=x_0+2}^{x=\infty} \frac{I_x}{I_1} \cdot \frac{E_x}{E_n} \cdot \frac{x}{x^2 - n^2}$$

The lower section is summed term by term to give as good an approximation as possible, while for the higher section a general upper limit can be found for all cases.

Thus from Equation (21), Appendix 5, we have

$$\psi_2 = \frac{r}{\omega L} \sum_{x=x_0+2}^{x=\infty} \frac{I_x}{I_1} \cdot \frac{E_x}{E_n} \cdot \frac{x}{x^2 - n^2}$$
$$\leqslant \frac{r}{\omega L} \cdot \frac{0 \cdot 577a}{\sin n\alpha(1 - \cos n\alpha)} \log_{10} \frac{1}{1 - (n/x_0)^2}$$
$$\therefore \ \psi = \psi_1 + \psi_2$$
$$\leqslant \frac{r}{wL} \left\{ \left(\sum_{x=1}^{x=x_0} \frac{I_x}{I_1} \cdot \frac{E_x}{E_n} \cdot \frac{x}{x^2 - n^2} \right) + \left(\frac{0 \cdot 577a}{\sin n\alpha(1 - \cos n\alpha)} \log_{10} \frac{1}{1 - (n/x_0)^2} \right) \right\} \quad . \quad (6)$$

In evaluating the separate terms of the lower section of the series, E_x/E_n may be replaced by A_x/A_n, the ratio of corresponding harmonics in the limiting triangular wave, with a close degree of approximation, provided that x and n are less than 27 if α is taken as 6°. The slight error introduced by taking A_x/A_n for E_x/E_n in the terms for which $x = 27$ and $x = 29$ will not appreciably affect the value of the total error, as the major portion of this is due in most cases to the terms of the fundamental and lower harmonics.

The maximum possible value of the total error depends of course on the magnitudes of the various harmonics in the wave-form being analysed, and so this maximum value of ψ has been worked out for five, more or less standard, cases for an r/L of 15 and a fundamental frequency of 50.

The five particular wave-forms considered are as follows :—

(i) The rectangular wave in which $I_x/I_1 = 1/x$. It has been shown previously that this wave-form is much worse than any likely to be met with in practice.

(ii) A wave in which all the harmonics up to and including the 19th are 5 per cent of the fundamental, and the remainder have the same amplitudes as in the rectangular wave, i.e. $(100/x)$ per cent of the fundamental.

(iii) A wave in which all the harmonics except the 9th, 11th, 19th, 21st and 29th are less than 1 per cent or $(100/x)$ per cent of the fundamental, whichever is the smaller, while these five particular harmonics have amplitudes $(100/x)$ per cent of the fundamental.

For all these cases x_0 has been taken as 29 when finding harmonics up to and including the 17th, while for the 19th, 21st and 23rd harmonics it has been taken as 35 in order to keep to a fairly close degree of approximation throughout.

Since the factor $\cos \theta_x$ in each term of the series for the actual error may have any value between -1 and $+1$, it is probable that in general the actual error will not exceed about one-fourth of the maximum value calculated. Thus, with perhaps the exception of the third harmonic, the error anticipated will not exceed about 0·1 per cent of the fundamental for a ratio r/L of 15 for the oscillatory circuit and a frequency of 50 for the wave under analysis. In the determination of the 9th and higher harmonics the actual error may conceivably be much less than 0·1 per cent of the fundamental, as the maximum possible error will not in general exceed 0·25 per cent of the fundamental.

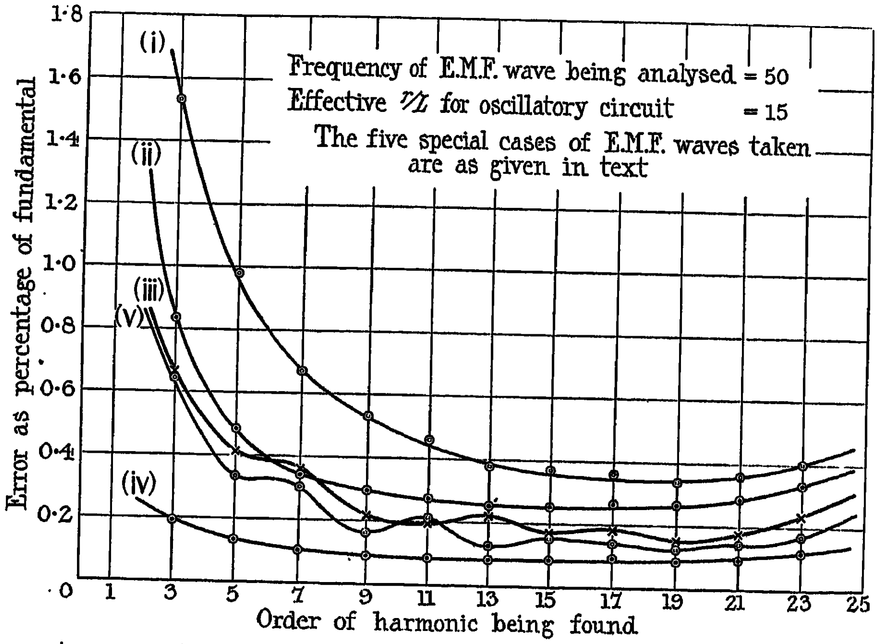

FIG. 18.—The maximum error in the dynamometer reading, due to the analysing current not being sinusoidal, given for the analysis of several different E.M.F. waves.

This case might be considered to correspond to that of an alternator having a very pronounced tooth ripple of low order. The lower the order the greater is likely to be the error introduced.

(iv) A wave in which all the harmonics are less than 1 per cent or $(100/x)$ per cent of the fundamental, whichever is the smaller.

(v) The wave-form of phase voltage of the three-phase Kolben alternator as analysed by the standard method. The results given in Table 2 are taken for harmonics up to the 23rd, and beyond this it is assumed that the harmonics do not exceed 3 per cent or $(100/x)$ per cent of the fundamental, whichever may be the smaller. The results giving the error as a percentage of the fundamental are embodied in Fig. 18.

(e) *Note on wave-form of analysing current.*—Oscillograph records of the resonating voltage across the main inductance for the oscillatory circuit tuned to various harmonics in the induced E.M.F. wave are given later in Fig. 19. From these it is seen that the form of the resonating voltage and therefore of the analysing current is in general that of a series of trains of damped oscillations, each train commencing with the impulse of E.M.F. induced in the circuit.

During the period between two successive impulses the circuit oscillates at its natural frequency, the current following a law of the form

$$i = I_0 e^{-r/2L} \sin n'\omega t$$

where $n' = \sqrt{\{n^2 - r^2/(4\omega^2 L^2)\}}$, and so differs very little from n, the order of the harmonic to which the circuit is tuned. Thus the current gradually changes its phase

with regard to the corresponding harmonic in the induced E.M.F. wave, until with the next impulse of E.M.F. the initial phase relations are again restored.

It might at first be thought that our previous theory is invalid, since there we considered undamped waves throughout. It will be seen, however, that the wave-form of oscillatory current is periodic in twice the time between two successive impulses of E.M.F., and hence, taking this as the fundamental period, we may resolve the trains of damped oscillations into their undamped Fourier components, to which the preceding theory does apply without modification.

(*f*) *Details of apparatus and experimental methods.*—The final method of analysis adopted, in which the whole apparatus is portable, is based on the neon-lamp method at present being described. In this original neon-lamp method serviceability and portability were not premier considerations, as it was only desired to obtain practical results to verify the principles underlying the method. The actual form of the apparatus used, in which essentially laboratory methods of measurement were employed, will here be described.

The temporary apparatus used for the justification of this method differed from that used in the standard method employing a commutator, but only in the means of excitation of the oscillatory circuit.

The full diagram of connections is shown in Fig. 13. The transformer used was a small instrument transformer, rewound to give a high secondary voltage, with a ratio of transformation of 1 to 12. The choke coil in the primary circuit was such that with no rheostat resistance in circuit a current of about 10 amperes was taken from the a.c. supply at about 200 volts, this being sufficient to saturate the core of the transformer over the greater part of the cycle, and giving an R.M.S. voltage of about 30 volts across the primary winding. A maximum secondary voltage of about 2 000 was obtained, owing to the very peaked nature of the wave-form.

The neon-filled glow-lamps employed were the 5-watt "Osglim" lamps for use on a 220-volt d.c. circuit. It was found convenient to use four of these in series, two pairs, with those of each pair "back to back," this enabling us to induce a symmetrical E.M.F. wave in the oscillatory circuit, as already explained.

The air-core mutual inductance, by means of which the desired E.M.F. wave was induced in the oscillatory circuit, consisted of a primary coil having about 5 000 turns of fine wire and a mean diameter of about 15 cm, a secondary with about 30 turns of stranded wire, and a d.c. resistance of 0·12 ohm. As previously pointed out, owing to short-circuits that developed in the main coil this had a ratio r/L of 50 instead of 10, for which it was designed. The ratio r/L for the whole oscillatory circuit was increased to 70 by the secondary of the coupling when the large coil was connected with all its layers in parallel to give a minimum self-inductance.

The remainder of the apparatus was as in the standard method, the resonating voltage across the main inductance being observed by the use of an electrostatic voltmeter in conjunction with a potential divider, while the deflection of the dynamometer whose fixed coil was the main inductance of the oscillatory circuit was observed by means of the reflecting system already described.

The general method of test for the analysis of an E.M.F. wave is as follows :—

The transformer is energized from the same source of a.c. supply as the wave-form being analysed. The choke coil in the primary circuit is adjusted so that a

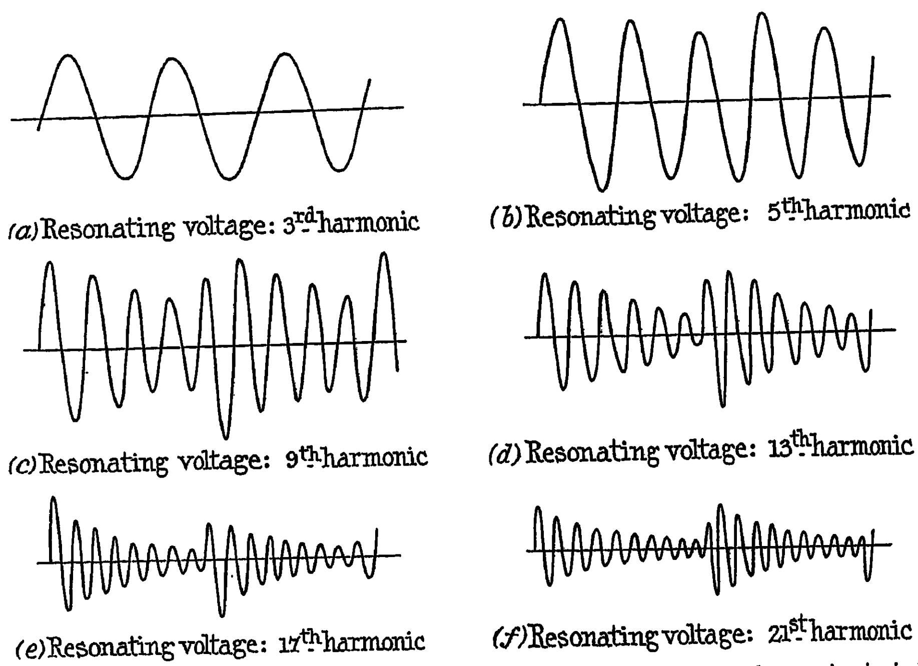

FIG. 19.—Wave-forms of resonating voltage, with oscillatory circuit tuned to various harmonics in induced E.M.F.

current sufficient to saturate the core is obtained, in this case about 10 amperes. The peaks in the wave-form of voltage across either of the transformer windings are most pronounced when the primary current is maintained as nearly as possible sinusoidal. Thus we use a choke coil in the primary circuit in preference to a resistance, and also keep the R.M.S. voltage across the primary of the transformer less than about 20 per cent of the supply voltage. This necessitates an a.c. supply at about 200 volts for the particular transformer used. Should the supply voltage be much less than this, it may be advisable to have it stepped up first by an ordinary transformer.

The number of neon lamps used in the secondary circuit of the transformer must be such that the maximum harmonic in the E.M.F. wave induced in the oscillatory circuit is about the 11th or 13th.

The oscillatory circuit is tuned to the harmonic in the induced E.M.F. of the same order as that to be found in the wave under analysis, the electrostatic voltmeter giving a maximum reading when the circuit is exactly tuned.

The magnitude of the harmonic is found from the resonating voltage and the reading of the dynamometer. We may eliminate the term $\cos(\phi_n - \phi_n')$ either by adjusting the phase of the current in the primary circuit of the transformer until the dynamometer reading is a maximum (a non-inductive resistance being in series with the pressure coil), or by taking two readings of the dynamometer with a non-inductive resistance and a small-capacity condenser respectively in series with the pressure coil.

In the former case the phase of the current is changed by introducing resistance into the primary circuit of the transformer; and at the same time reducing the reactance of the choke coil to keep the current constant.

Then with the same notation as in Equation (5*f*) of Section 5 we have :—

$$d_{max.} = DN\frac{e_n}{Z}$$

N can be found from the resonating voltage V_n, thus

$$N = \frac{V_n}{n\omega L} \times (\text{No. of turns in series})$$

and hence e_n can be determined.

In the second case in which the double-reading method is employed, if d_1 and d_0 are the two dynamometer readings obtained with series resistance and capacity respectively, we have :—

$$d_1 = DN\frac{e_n}{Z_1}\cos\theta_n$$

$$d_0 = DN\frac{e_n}{Z_2}\cos(\theta_n + \tfrac{1}{2}\pi) \text{ approx.}$$

$$= DN\frac{e_n}{Z_2}\sin\theta_n$$

If $$\frac{d_1 Z_1}{DN} = e_1 \quad\text{and}\quad \frac{d_0 Z_2}{DN} = e_2$$

then $$e_n = \sqrt{(e_1^2 + e_2^2)}$$

Although the latter method was used throughout the tests made with this neon-lamp method of analysis, it was used only because it was more convenient at the time, for it was found rather difficult to change the phase of the current by adjusting the resistance and choke coil so that the magnitude of the current remained unaltered, and at the same time to watch for the maximum dynamometer deflection through the telescope.

In the final method of analysis adopted, the phase-changing method is recommended for obtaining the dynamometer deflection. The advantage of this method is that only one reading is necessary for each harmonic, and the possible error is not greatly increased if the reading is taken with the resonating current not quite at its maximum value, whereas with the double-reading method it is essential to tune the circuit exactly for each of the two readings, as otherwise there may be quite an appreciable change in the phase of the resonating current if the frequency changes slightly.

(*g*) *Further possible sources of error.*

(i) In the latter method of finding the harmonic by a double reading of the dynamometer an error will be introduced, due to the phase of current in the pressure coil circuit not being changed by quite 90°.

It can be shown that the fractional error due to this cause lies between the limits $\pm \frac{1}{2}\sin\beta$, where β = angle of phase difference from perfect quadrature. Details of the calculation involved are not given, as this double-reading method was finally superseded.

On inserting the values of the pressure-coil constants, β was found to be 6° 41′ for the 23rd harmonic, giving an error of 5·8 per cent of this harmonic.

As this error increases with the order of the harmonic, it is in general quite small compared with the error due to unsinusoidal analysing current, which for the higher harmonics may have been as much as 0·5 per cent of the fundamental for the inductance coil used.

An additional error may be caused in this method if the frequency changes between the two readings, for in this case the circuit has to be re-tuned for the second reading and the phase of the current may be changed by a small amount relative to that of the induced E.M.F., owing to the fact that it is impossible to ensure that the current is exactly in phase with the E.M.F. in either of the two cases. The amount of this possible phase-change depends on the sensitivity of the instrument measuring the resonating voltage. For an instrument that can be observed to 1 part in 500 the maximum possible error may be increased for all harmonics by about 3 per cent of the harmonic. Even this, however, is not serious.

(ii) When using a condenser in series with the pressure coil we alter I_x/I_1 from its value when employing the series resistance, and so alter the terms in the expression for the error in the dynamometer reading. For all values of x less than n the terms are decreased, while for all values of x greater than n they are increased. This ratio of increase of corresponding terms has, however, an upper limit of $(R_p + r_p)/r_p$.

Thus, since in the original expression for the error the term due to the fundamental is perhaps the most important, it is reasonable to suppose that the resultant

error will not be increased when capacity is substituted for resistance in the pressure-coil circuit.

(iii) When using a series condenser in the pressure-coil circuit the current induced in this circuit by the fixed-coil flux is almost in phase with this latter, and so the mutual-inductance error may be relatively much more important than for the case of a series resistance, dealt with for the standard method in Appendix 4 (ii).

To ascertain whether this error was appreciable for the particular dynamometer and series condenser used, the most convenient method was adopted, namely, that of short-circuiting the pressure coil and its series condenser, passing a known current through the fixed coil, and observing the deflection of the moving coil for various initial positions.

The extra deflection observed was in all cases inappreciable and so the error due to this cause could be neglected.

(iv) All other possible sources of error have already been dealt with in connection with the standard method of analysis, it being shown that the magnitude of the error introduced is in every case negligible.

(*h*) *Results of tests.*—Oscillogram records of the resonating voltages across the main coil were obtained for most of the harmonics. The element of the oscillograph was connected direct to a small search coil which was placed sufficiently near to the end of the main inductance to give a reasonable deflection. Reproductions from the original tracings obtained with a Duddell low-frequency oscillograph are shown in Fig. 19.

Two E.M.F. waves were analysed by the neon-lamp method described, namely the phase and line voltages of the three-phase Kolben alternator, as analysed by the standard method. The supply to the saturated transformer was the only load on the machine during the tests.

The analysis was not carried beyond the 17th harmonic in either case, as sufficiently large resonating currents could not be obtained. This was due to the fact that at the time of the test the primary and secondary circuits of the saturated transformer had not been properly adjusted to give a sufficiently small arc of current in the latter circuit, with the result that the higher harmonics in the E.M.F. wave induced in the oscillatory circuit decreased far too rapidly.

The results obtained are given in Table 4. The results obtained by the standard method of analysis are, for purposes of comparison, also included in this table.

(*i*) *Conclusions.*—From the results it is seen that the error is less than 0·5 per cent of the fundamental except in the case of the 17th harmonic, for which it is 0·54 per cent. The larger error for the higher harmonics can be attributed partly to imperfect quadrature adjustment and partly to the experimental error of reading, since for these harmonics the dynamometer deflections were comparatively small. Also, owing to inferior dielectric, the losses in the small tuning condenser were much larger than originally anticipated. From a previous discussion of this point in connection with the standard method it is probable that for the particular condensers used the increase in the effective ratio r/L for the oscillatory circuit may easily have been as much as 50 per cent at the frequency of the 17th harmonic.

As already pointed out, the first error can be eliminated altogether in the final method if we use that method of dynamometer reading in which the phase of the primary current of the saturated transformer is adjusted to give a maximum dynamometer deflection.

The most important information derived from the test-results is the relation between the maximum error and the effective r/L for the circuit. Thus a maximum error of 0·5 per cent of the fundamental was obtained for a ratio r/L of not less than 70 at a fundamental frequency of 45. From this we may deduce that to measure the harmonics in an E.M.F. wave correct to within 0·1 per cent of the fundamental, we require an oscillatory circuit with an effective ratio r/L of 15.

That method of obtaining the dynamometer reading in which the phase of the current is changed will be used as before mentioned, and the sensitivity of the dynamometer will be increased so much that a telescope will no longer be required.

TABLE 4.

Analysis of Phase and Line Voltages of Three-phase Kolben Alternator at 45 Cycles per second.

Order of harmonic	Phase voltage, per cent		Line voltage, per cent	
	Dynamometer method (neon lamps)	Standard method	Dynamometer method (neon lamps)	Standard method
	per cent	per cent	per cent	per cent
1	100·0	100·0	100·0	100·0
3	10·2	10·0	0·4	0·53
5	6·1	6·0	6·1	5·7
7	0·45	0·24	0·6	0·2
9	7·3	7·5	0·5	0·04
11	3·1	2·7	3·2	—
13	5·3	5·1	5·6	5·2
15	1·8	—	0·6	—
17	0·9	0·62	1·2	0·66

The actual readings of the dynamometer and the voltmeter measuring the resonating voltage, and in fact the actual design of these instruments, will depend on the magnitudes of the resonating currents that it is possible to obtain for the various harmonics, and so mention will here be made of the chief factors limiting the resonating current.

The relative magnitudes of the resonating currents that can be obtained for the various harmonics depend on the harmonics in the induced E.M.F. wave. This question has already been dealt with.

The actual magnitude of any harmonic in the oscillatory circuit with this tuned to a given harmonic will depend largely on the original E.M.F. in the neon-lamp circuit, modified by the back E.M.F. induced in this circuit by the harmonic of current being considered in the oscillatory circuit. The former depends on the peak voltage given by the secondary of the transformer, while the latter depends on the magnitude

of the coupling between the neon-lamp and oscillatory circuits.

For all harmonics other than that to which the oscillatory circuit is tuned, the current in the oscillatory circuit is comparatively small, so that the back E.M.F. induced in the neon-lamp circuit is negligible compared with the corresponding harmonic in the E.M.F. given by the saturated transformer. Thus the given harmonic of current in the neon-lamp circuit remains unaltered, and the current of the same harmonic in the oscillatory circuit is proportional to the coupling or mutual inductances M_1.

In the case of the resonating harmonic, however, the back E.M.F. becomes the predominating factor if M_1 is too large; for then the neon-lamp current of the resonating harmonic is reduced, and so in the oscillatory circuit the resonating harmonic current is reduced relative to the other harmonics. This is equivalent to an increase in the effective ratio r/L for the oscillatory circuit, and this is to be avoided as far as possible. For this reason it will not be advisable to increase M_1 to such a value that the back E.M.F. is appreciable, i.e. the coupling must not be increased beyond the point at which the resonating current is proportional to the value of M.

It is interesting to note that the magnitude of the back E.M.F. induced in the neon-lamp circuit by the oscillatory current is not as great as might at first sight be anticipated, for owing to the peculiar characteristic of the neon lamp this reaction is only effective over approximately that small part of the cycle during which current flows in the lamp circuit. As a result of this it can be shown, by resolving this discontinuous reaction into its various harmonics, that the back E.M.F. is the same as with a coupling for which the inductance $M_1' = M_1 \frac{4}{\pi}\left(a - \frac{\sin 4na}{4n}\right)$ where the reaction is effective over the whole cycle. Thus for $a = 6°$ and $n = 3$, $M_1' = 0{\cdot}032\, M_1$; while for $n = 23$, $M_1' = 0{\cdot}146\ M_1$. Thus the reaction is less for the lower harmonics.

Whilst it is possible to work out theoretically the value of M_1 which must not be exceeded, it is much simpler to ascertain it experimentally by varying the coupling and finding the corresponding values of the resonating voltage for given conditions in the neon-lamp circuit.

Thus it was found that the coupling used in the tests described in this section by no means represented the limit possible. The ultimate limit could not be found, owing to lack of sufficient suitable inductance, but it was shown to be greater than 8 times the inductance of the coupling used in the tests.

With more power available in the oscillatory circuit it should be possible to use less sensitive and therefore more portable forms of instruments without greatly increasing the damping of the oscillatory circuit.

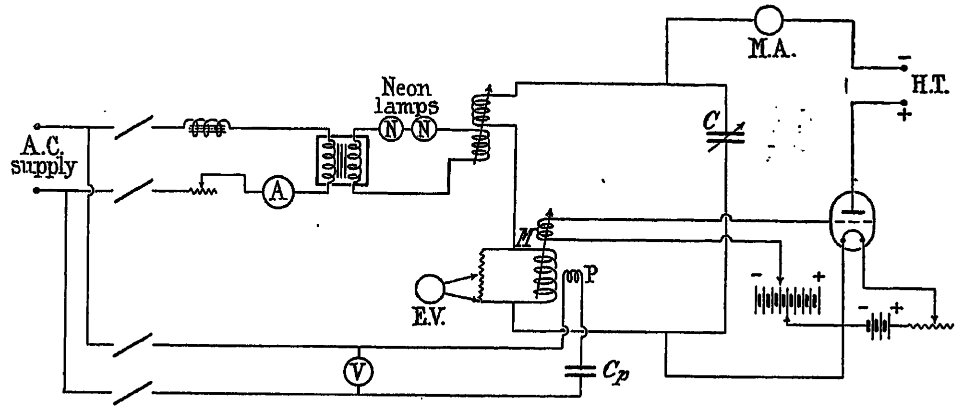

FIG. 20.—Diagram of circuit used in the tests.
M.A. = d.c. milliammeter. E.V. = electrostatic voltmeter.

7. THE FINAL METHOD OF ANALYSIS, WHICH IS ESSENTIALLY THE NEON-LAMP METHOD MADE PORTABLE BY THE USE OF A VALVE AMPLIFIER.

(*a*) *Introduction.*—The accuracy of the neon-lamp method of analysis has already been shown to depend on the effective ratio r/L for the oscillatory circuit, and so this accuracy can be increased considerably by using a 3-electrode valve circuit which, as is well known, can be made to act as a negative resistance. At the same time, as the oscillatory circuit can be designed for a much larger r/L than was before possible for the required accuracy, the whole apparatus can be made portable.

The discussion in this section of the paper will be chiefly limited to the establishing, theoretically and practically, of the fact that the 3-electrode valve can be used for the desired purpose.

While the apparatus used in the tests has been changed considerably from that of the previous methods, slight modifications in details have still to be made in order that it shall meet ordinary commercial requirements, and so a minute description of the apparatus will not be attempted.

(*b*) *The valve circuit employed, and the theoretical effect of this circuit on the effective ratio r/L for the oscillatory circuit.*—The valve circuit used is shown in Fig. 20. This is perhaps the simplest of all the

possible valve circuits, but it was also found to be the most suitable, both from theoretical considerations and as a result of practical familiarity with the various alternative circuits. Theoretically this is the best circuit, as it is the only one in which the effective resistance of the oscillatory circuit is independent of small changes in frequency. We require a circuit which gives an effective resistance independent of frequency, as otherwise the circuit may become self-oscillatory for even a slight fluctuation in the supply frequency, and when this occurs the dynamometer reading can no longer be interpreted as before.

Considering one harmonic only, in other words dealing with a sinusoidal current, we can obtain a mathematical expression for the effective resistance of the oscillatory circuit to the nth harmonic to which it is tuned, in terms of the constants of the circuit and valve used. We can also find the effective impedance to the xth harmonic current and hence determine the increase in the nth harmonic relative to the xth harmonic, which gives the decrease in the effective ratio r/L for the oscillatory circuit.

If the valve is worked on the middle portion only of its characteristic, and the variations in grid and anode voltage are limited so that only the straight portion is worked on, then

$$\frac{\partial i_a}{\partial v_g} = \text{constant} = g; \quad \text{and} \quad \frac{\partial i_a}{\partial v_a} = \text{constant} = a;$$

where i_a = current entering valve at anode,
v_a = voltage of anode above filament,
v_g = voltage of grid above filament.

With this notation it is shown in Appendix 6 that the effective resistance of the oscillatory circuit is reduced from r to $[r - (gM - aL)/C]$ by the use of the valve, where M = mutual inductance between grid coil and choke coil. This is of course the only impedance to the nth harmonic current.

The approximate impedance to the xth harmonic is shown to be $j\dfrac{x^2 - n^2}{x}\omega L$, this impedance being unchanged by the action of the valve.

Thus $\dfrac{I_n'}{I_x'} = \dfrac{E_n}{E_x} \cdot \dfrac{x^2 - n^2}{x} \cdot \dfrac{\omega L}{r - (gM - aL)/C}$ and so is increased by the ratio $\dfrac{r}{r - (gM - aL)/C} = A$, the amplification factor, and is the same as for a circuit with no valve amplification but with an effective resistance $r - (gM - aL)/C$.

(*c*) *Details of apparatus used.*—The full diagram of connections for the whole apparatus used in the tests made with this method has already been given in Fig. 20. As already pointed out, the apparatus will not be described in great detail as it has still to be modified in several respects. The chief difference from the previous method is in the oscillatory circuit and in the method of measuring the resonating current. The saturated transformer and supply to the neon lamps was essentially unchanged.

The inductance in the oscillatory circuit was divided between two equal coils, one of these being used as the fixed coil of the dynamometer while the other was used for coupling purposes with the neon-lamp circuit. Each coil was designed to have an r/L of 50, and was wound with an average of about 150 turns per layer of single-strand enamel-insulated wire, the exact number of turns per layer being adjusted to give an even distribution of current at all frequencies between the layers when these were connected in parallel. The considerations affecting the design of these coils were exactly as for the case of the original coil used, which case has already been fully dealt with in Section 5(*c*) of this paper. The design details of one of the coils used in the present method are given in Appendix 3. The linear dimensions of the coils were rather less than half those of the original coil used.

Each coil was divided permanently into four equal sections, each consisting of 10 layers connected in parallel. By means of plug connections these sections could be connected as desired, in series, series-parallel, or parallel, giving inductances of 0·0983, 0·0239, 0·0058 henry respectively.

The primary of the coupling with the neon-lamp circuit consisted of 14 layers wound on the outside of one of the main inductance coils, each layer consisting of 145 turns of enamelled wire with an approximate inductance of 0·006 henry. Connections from the ends of each layer were brought out to valve-holders, so that the neon-lamp current could be sent through any desired number of layers by plugging into two suitable valve-leg sockets.

The main condenser was of 10 μF in steps of 2 μF, which enabled the circuit to be tuned if desired to the 3rd harmonic of any a.c. supply with a frequency greater than 35. Together with a 1 μF condenser the tuning was done on a Tinsley variable condenser giving a range from 0·01 μF to 1 μF on a single-dial switch.

To keep the damping factor of the oscillatory circuit as low as possible, that main inductance not used as a coupling with the neon-lamp circuit was used as the fixed coil of the dynamometer by suspending the pressure coil in it. To secure the necessary sensitivity and stability the suspension ligaments passed through a hole in the top of the coil to an outside support. The deflection was found by the use of a reflecting system with a scale 1 m from the moving coil. The pressure coil consisted of 450 turns and had a resistance of 140 ohms, an inductance of 0·0161 henry, and a time period of approximately 2 seconds.

The grid coupling was a coil which could be rotated at the end of the dynamometer main inductance so that its mutual inductance with the oscillatory circuit could be varied. As no current is taken by the grid if the anode voltage is sufficiently high, the field of the dynamometer will not be affected. It is advisable to couple the grid with the dynamometer inductance rather than with the neon-lamp inductance, as in the latter the flux contains larger undesired harmonics than does the resonating current itself, owing to the effect of the neon-lamp current. In particular, the fundamental in the neon-lamp current is not inappreciable and so its amplification should be avoided. The grid coupling coil had a mean diameter of 6 in., con-

sisted of about 5 000 turns of fine wire, and had an inductance of about 1 henry. For an amplification of 4 with the 3rd harmonic of a 50-cycle supply, the angle between the axes of the coils had to be about 15°, while for the same amplification of the 21st harmonic it had to be increased to about 80° owing to the reduced mutual inductance required.

For most of the tests carried out with this method the resonating voltages across the fixed coil of the dynamometer were obtained by the use of the same electrostatic voltmeter and potential divider as were employed in all the previous methods. As an electrostatic voltmeter could not form part of the final apparatus it was replaced in several of the tests by a Moullin thermionic-valve voltmeter * which was found to be quite satisfactory for the purpose. The form

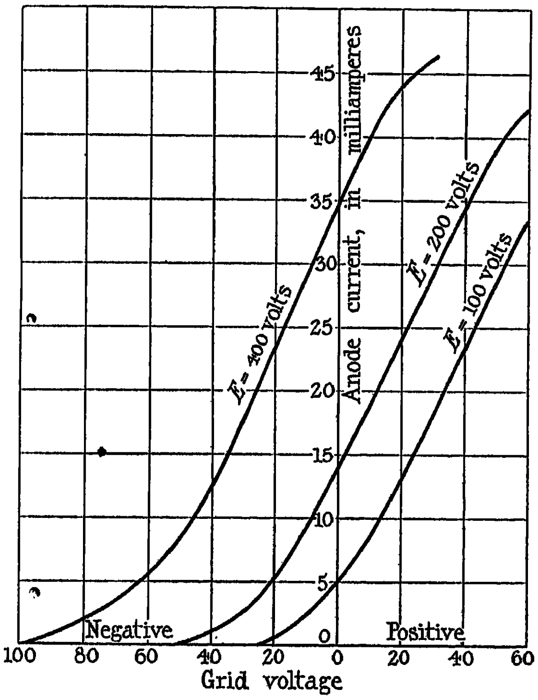

FIG. 21.—Grid voltage/anode current characteristics of the Marconi "LS2" valve used in the tests.

of this voltmeter found most suitable was that in which the a.c. voltage to be measured, and which is applied to the grid, is rectified by means of the grid potential anode-current characteristic, and measured by a d.c. milliameter in the anode circuit. No high-tension battery is required for the anode, which is connected through the ammeter to the positive end of the filament. This voltmeter has of course to be calibrated for the particular valve used, which in this case was a Marconi "R" type valve. This type of voltmeter is not independent of the wave-form, but as the voltage across the swinging circuit is very nearly sinusoidal no appreciable error is introduced. Experiments were made to compare the readings when an electrostatic voltmeter was used and when the Moullin voltmeter was used, the wave-form of the voltage in the moving coil being widely different, and no difference was detected.

Several types of valves were used for amplifying the oscillatory current, but of those tried the Marconi "LS2" valve was found to be the most suitable. This valve was worked with 5·2 volts on the filament, while for the anode circuit the ordinary d.c. supply at 220 volts was used, although a higher voltage would have given better results had it been available.

The characteristics of the valve used are shown in Fig. 21 for anode voltages of 100, 200 and 400 respectively.

(*d*) *Experimental methods.*—Before an actual analysis could be carried out, the transformer and neon-lamp circuits had first to be adjusted so that the desired wave-form of E.M.F. was induced in the oscillatory circuit. This was done as a preliminary test by passing the neon-lamp current through an oscillograph and adjusting the circuit conditions until the duration of neon-lamp current in each half-cycle had the appropriate value. The suitability of the E.M.F. wave obtained for given circuit conditions could also have been judged by calculating harmonics in this E.M.F. wave from the magnitudes of the various resonating voltages.

In the final commercial form of the apparatus there will be no need for a preliminary test of this description, as the transformer and neon-lamp circuits will be so designed that the desired conditions can be obtained by an adjustment of the primary current.

For the apparatus used, the current taken from the a.c. supply was about 10 amperes, although this figure could be greatly reduced by a suitable design of the saturated transformer.

Initially there was no rheostat resistance in the supply circuit, the impedance being almost entirely choke-coil reactance.

The neon-lamp current was passed through the desired numbers of layers of the coupling with the oscillatory circuit by plugging into valve-leg sockets as already explained. As it was desirable, for reasons already given in Section 6(*i*), to know whether the maximum mutual inductance obtainable between the neon-lamp and oscillatory circuits caused too great a reaction between these circuits, a special test was performed. The number of layers of the primary of this coupling through which the neon-lamp current was passed was varied, and the corresponding resonating current found, with the circuit tuned to a given harmonic. The resonating current was found to be proportional to the number of layers of the coil through which the neon-lamp current was passed, that is, to the mutual inductance with the oscillatory circuit up to the maximum mutual inductance obtained with all 14 primary layers in series. The result showed that it was not necessary to limit the coupling to prevent excessive reaction between the circuits. However, in the analysis tests afterwards carried out it was found advisable to pass the neon-lamp current through only two layers of the primary of this coupling, since when a larger coupling was employed the unamplified oscillating current obtained was too large to allow the

* E. B. MOULLIN: "A Direct-Reading Thermionic Voltmeter, and its Applications," *Journal I.E.E.*, 1923, vol. 61, p. 295.

desired amplification to be obtained by the valve as then used.

For the complete analysis of a wave-form, the harmonics are most conveniently worked through in order, starting with the 3rd, for which the approximate capacity required can be calculated. The phase of the current in the supply to the transformer is changed until a maximum reading of the dynamometer is obtained, the oscillatory circuit having been tuned to the desired harmonic. This phase change is effected by inserting resistance in the supply circuit to the transformer and at the same time reducing the reactance of the choke coil to maintain the current constant. In the final apparatus, in order to avoid complication, these adjustments can no doubt be made together by some suitable device, such as a small phase-changing transformer. Owing to the small variation in phase required for the higher harmonics it is only necessary to vary the resistance above about the 9th harmonic. Readings are taken of the maximum dynamometer deflection d'_n, the corresponding resonating voltage v'_n, and the voltage e' of the a.c. supply. The neon-lamp coupling is then disconnected, the valve filament lighted, and the grid coupling adjusted so that the circuit is almost—but not quite—oscillating. The neon-lamp coupling is then remade, the oscillatory circuit again tuned up (the tuning now being much sharper), the phase of the current readjusted if necessary and a further set of readings taken of all three instruments. In the tests made, an amplification of 4 times was obtained without difficulty for all the harmonics, although it could not be greatly exceeded with the valve used.

If d''_n, v''_n and e'' are the respective instrument readings with the amplified current, the readings of both voltmeters being given as R.M.S. values, then

$$d' = ki_n\frac{v'_n}{n\omega L_1},$$ where i_n is the R.M.S. current of nth harmonic in the pressure coil, and k is the d.c. calibration constant of the dynamometer.

$$d'' = ki_n\frac{e''}{e'}\cdot\frac{v''_n}{n\omega L_1}$$

$$\therefore \frac{e'}{e''}d'' - d' = \frac{ki_n}{n\omega L_1}(v''_n - v'_n)$$

$$\therefore \quad i_n = \frac{n\omega L_1}{k}\cdot\frac{\left(\frac{e'}{e''}d'' - d'\right)}{v''_n - v'_n}$$

But $i_n = e_n n\omega C_p$ (approx.), where e_n is the harmonic being found in the E.M.F. wave, and C_p = the capacity in series with the pressure coil.

$$\therefore \quad e_n = \frac{L_1}{kC_p}\cdot\frac{\left(\frac{e'}{e''}d'' - d'\right)}{v''_n - v'_n}$$

$$= K\cdot\frac{\left(\frac{e'}{e''}d'' - d'\right)}{v''_n - v'_n},$$ where $K = \frac{L_1}{kC_p}$ and so depends on the range of inductance used, and on the capacity of the condenser used in series with the pressure coil.

In general the a.c. supply voltage will not change between the two sets of readings, in which case $e'/e'' = 1$.

Since when using a series condenser in the pressure-coil circuit the final result, e_n, is independent of frequency, a change in frequency between the two sets of readings will not affect the accuracy of the result. Thus it is not necessary to know the frequency in order to calculate the magnitude of a harmonic, and so a frequency meter is not essential.

The dynamometer sensitivity was such that, in general, reasonably large deflections could be obtained for a series capacity of only 0·2 or 0·1 μF. In any case it was desirable to use the 0·1 μF condenser for the higher harmonics in order to reduce the error due to the impedance of the pressure-coil circuit being taken as $1/n\omega C_p$, that is, of course, if this error, which is dealt with in Section 7(*e*)(vi) of the paper, is comparable with the error of reading.

One of the advantages of taking two sets of readings and using their difference is that any zero error which there may be is thereby eliminated.

It is desirable that the valve used for amplifying shall not be worked too far beyond the straight portion of its characteristic. A range of grid voltage corresponding to about 0·8 of the anode saturation current is shown in Section 7(*e*)(ii) of the paper not to be excessive. This may be ensured either by calculating the limiting resonating voltage in terms of the limiting grid voltage and the constants of the valve and oscillatory circuit, or by keeping the resonating voltage less than about 80 per cent of the value when the circuit is just oscillating and at the same time working the valve at the middle part of its characteristic, or by working the valve rather below its mid-point and including in the anode circuit a d.c. milliameter, whose indication will begin to increase when the range of grid voltage passes beyond the straight portion of the characteristic.

It might be thought that a considerable increase could be effected in the oscillatory current by using the synchronizing property of coupled valve generators,* since by this property the oscillations in a self-oscillatory circuit can be kept exactly "in step" with an induced E.M.F. whose frequency does not differ from the natural frequency of the oscillatory circuit by an amount greater than that given by

$$\frac{\delta\omega}{\omega} = \frac{1}{\sqrt{2}}\cdot\frac{e_0}{A_0}$$

where e_0 = E.M.F. impressed from outside,
and A_0 = natural amplitude of voltage across oscillatory circuit.

This property cannot be made use of, however, since in the range $p - \delta p$ to $p + \delta p$ for the impressed E.M.F. there is a change in phase of the current in the oscillatory circuit relative to that of the impressed E.M.F. from $-\frac{1}{2}\pi$ to $+\frac{1}{2}\pi$, so that any slight fluctuations in the supply frequency would cause such

* E. V. Appleton: *Proceedings of the Cambridge Philosophical Society*, 1922, vol. 21.

excessive variations in the dynamometer reading that this would be valueless.

The error due to the mutual-inductance effect between the fixed and moving coils of the dynamometer was found to be so small that it was not worth correcting for, as the increase in the deflection due to this cause was less than the error of the reading.

The positions of the iron-cored choke coil in the transformer supply and the neon-lamp coupling, relative to the dynamometer coil, were adjusted for the tests made so that the influence on the deflection of the latter due to stray fields was negligible.

The theory, which forecasted that only the resonating harmonic of the oscillatory current would be amplified, was justified by the test-results obtained, which showed that when the harmonic in the wave being analysed was negligible there was no sensible change in the dynamometer deflection, although this deflection itself might be quite appreciable if the neighbouring harmonics were large. Also the same value for the harmonic was obtained for widely different couplings and resonating voltages.

(*e*) *A theoretical consideration of the various sources of error.*

(i) *Error in dynamometer reading due to the analysing current not being sinusoidal.*—By taking two sets of readings for each harmonic, one before and one after amplification, and calculating the magnitude of the harmonic from the differences of these readings, the dynamometer error is reduced as shown in Appendix 7 to $\frac{3}{8}r/(A\omega L)$ of the value it would have were the harmonic calculated from the single set of readings obtained with the amplified current.

Actually the maximum error is smaller than $[r^2/(40A\omega L)]\psi_n$, where ψ_n is the maximum value of the error in the original single-reading method for an r/L of 15. Thus taking $r/L = 100$, and $A = 4$, tests having shown the latter to be a reasonable figure,

$$\text{max. error} < 0\cdot2\,\psi_n$$

For most waves likely to be analysed, the maximum possible error must therefore be less than 0·1 per cent of the fundamental, which means that the average error likely to be obtained in practice will not exceed about 0·025 per cent of the fundamental, and so in general will be negligible compared with the errors of reading.

For the actual oscillatory circuit used in the tests made with this apparatus, the ratio r/L was considerably increased for the higher harmonics owing to large losses in the main condenser due to inferior dielectric.

For harmonics below the 7th the ratio r/L was probably not greater than 100, and so the maximum error would not have exceeded the figure given above. It was estimated that at the frequency of the 23rd harmonic the ratio r/L might have been as large as 300, which might have led to an average error of about 0·15 per cent of the fundamental. This source of trouble will be removed by a careful design of the condensers used.

(ii) *Error due to interfering harmonics in the analysing current produced by the valve when the latter is worked beyond the straight portion of its characteristic.*—If the valve is worked beyond the straight portion of its characteristic, a sinusoidal voltage applied to the grid will result in an anode current with the tops of its wave flattened, and so this current, and therefore the current in the oscillatory circuit, will contain harmonics of an order other than n.

It is shown in Appendix 8 that if the range of variation of the anode current is limited to about 80 per cent of the saturation current, and the valve is worked from the mid-point of its characteristic, then the only appreciable interfering harmonic induced in the oscillatory circuit will be one of order $3n$. Further, it is shown that due to this cause

$$\text{increase in } \frac{I'_{3n}}{I'_n} < \frac{rhV_g^2}{32n\omega Lg}$$

where V_g = max. value of grid voltage measured from mid-point of characteristic,

and g and h are coefficients determined by the equation

$$i_a = gv_g + hv_g^3 + av_a + bv_a^3$$

which gives a good approximation to the characteristic for a restricted variation of grid voltage, i_a, v_g and v_a being measured from the mid-point of the characteristic.

It is clear from Appendix 6 that this harmonic will not be amplified further by the action of the valve, and is therefore the only harmonic that need be considered for the error in this case.

For the valve used, namely a Marconi "LS2" valve, h/g was of the order of 5×10^{-5} if the valve was worked at the mid-point of its characteristic.

In the tests carried out with this method the valve was worked considerably below the mid-point of its characteristic, as a d.c. supply of only 220 volts was available for use in the anode circuit. Due to this the interfering harmonic was not greater than the value calculated using the ratio h/g as given by the lower portion of the characteristic. This value of h/g was 2×10^{-4}, while the corresponding value of V_g was 30 volts.

The addition to the error as a fraction of the fundamental owing to the presence in the oscillatory circuit of this extra $3n$th harmonic is

$$\frac{I_{3n}}{I_1}\cdot\frac{I'_{3n}}{I'_n}\cos\theta_{3n}$$

(from the general series for the dynamometer error)

$$\leqslant \frac{I_{3n}}{I_1}\cdot\frac{I'_{3n}}{I'_n}$$

This additional error will be greatest when determining the 3rd harmonic, in which case it will be $< 0\cdot0006 I_9/I_1$ for $\omega = 314$ and $r/L = 100$, and since in general we have

$$\frac{I_9}{I_1} < \tfrac{1}{9}$$

the addition to the error will be less than 0·01 per cent of the fundamental under these conditions. This is negligible compared with errors of reading and calibration.

(iii) *Error due to the voltmeter across the main inductance recording the R.M.S. value of the mixed*

wave and not the value of the resonating harmonic only, as assumed.—This is perhaps the chief source of error in this method, owing to the large ratio r/L which is not decreased by amplification for the first set of readings taken for each harmonic.

This error is shown in Appendix 9 to be given by

$$\frac{\delta I_n}{I_n} = \frac{1}{2A} \cdot \left(\frac{r''}{n\omega L}\right)^2 \sum_{x=1}^{x=\infty} \left(\frac{E_x}{E_n} \cdot \frac{x^2}{x^2 - n^2}\right)^2$$

where $\frac{\delta I_n}{I_n}$ = ratio of error to the actual value of the nth harmonic.

The infinite series in the above expression is shown to be convergent for such values of E_x/E_n as would be given by the neon-lamp circuit.

This error is greatest for the 3rd harmonic. For the lower harmonics it is approximately proportional to $1/n^4$, but in all cases it is less than the figure obtained by assuming it to be proportional to $1/n^2$.

Thus for an actual r/L of 100 and an amplification factor of 4, the error will be approximately 10 per cent of the harmonic itself for the 3rd harmonic, 2 per cent for the 5th harmonic, 0·5 per cent for the 7th harmonic, and so on. The error will therefore be negligible except in the case of the 3rd and 5th harmonics, but it should be possible to apply a correction in these cases so that the resulting error is not greater than 1 per cent.

For the oscillatory circuit used, r/L was found to have the approximate values 67, 83 and 96 respectively for the 3rd, 5th and 7th harmonics of a 50-cycle supply. Thus the error for the practical results obtained would be of the order of 4·5 per cent, 1·4 per cent and 0·40 per cent respectively for the 3rd, 5th and 7th harmonics.

If the oscillatory current is measured by means of an ammeter, the error for the lower harmonics is considerably reduced, being now

$$\frac{\delta I_n}{I_n} = \frac{1}{2A} \left(\frac{r''}{n\omega L}\right)^2 \sum_{x=1}^{x=\infty} \left(\frac{E_x}{E_n} \cdot \frac{nx}{x^2 - n^2}\right)^2$$

from which, for $r/L = 100$ and $A = 4$, the error would be 1·3 per cent, 0·8 per cent and 0·4 per cent for the 3rd, 5th and 7th harmonics respectively, and less for all higher harmonics. Thus if an ammeter were used to measure the oscillatory current, and r/L for the circuit did not exceed 100, this error would be negligible for all harmonics.

(iv) *Error due to the reading of the voltmeter across the a.c. supply being taken as due to the fundamental alone.*—Since the voltmeter across the supply being analysed records the R.M.S. value of the fundamental, together with all the harmonics present, a small error may be made by taking this reading as the value of the fundamental alone.

This error, which affects all harmonics in the same ratio, would be only − 1·5 per cent of the harmonic for the Kolben phase voltage as analysed, and, since in general it would be even less than this, it need not be corrected for.

In exceptional cases in which all the harmonics are not small compared with the fundamental, the voltmeter reading can be corrected from the values of the harmonics found to give a close approximation to the true value of the fundamental alone.

(v) *Error due to the impedance of the pressure coil in series with a condenser being taken as $1/(n\omega C_p)$.*

$$\text{Actually } e_n = i_n\sqrt{\left\{r_p^2 + \left(n\omega L_p - \frac{1}{n\omega C_p}\right)^2\right\}}$$

where

e_n and i_n = R.M.S. values of nth harmonics in a.c. voltage and pressure-coil current respectively,

r_p and L_p = resistance and inductance of pressure coil,

and C_p = capacity in series with pressure coil.

$$e_n = \frac{i_n}{n\omega C_p}\sqrt{\left\{1 + n^2\omega^2 C_p^2\left(r_p^2 + n^2\omega^2 L_p^2 - \frac{2L_p}{C_p}\right)\right\}}$$

$$= \frac{i_n}{n\omega C_p}\left\{1 + \tfrac{1}{2}n^2\omega^2 C_p^2\left(r_p^2 + n^2\omega^2 L_p^2 - \frac{2L_p}{C_p}\right)\right\} \text{ (approx.)}$$

Therefore error made in determination of e_n by taking $e_n = i_n/n\omega C_p$ is given by

$$\frac{\text{error}}{e_n} = -\tfrac{1}{2}n^2\omega^2 C_p^2\left(r_p^2 + n^2\omega^2 L^2 - \frac{2L_p}{C_p}\right) \text{ (approx.)}$$

This error increases with the order of the harmonic being found. For the pressure coil used, $r_p = 140$ ohms and $L_p = 0{\cdot}0161$ henry, and so, on substituting these values in the above expression, the error for the 23rd harmonic is given as 7·5 per cent of the harmonic itself for a series capacity of 0·1 μF. This error can be reduced by a suitable design of the pressure coil. Thus it can be reduced to one-half of the above value for the same sensitivity, by rewinding with half the number of turns of wire of double the cross-section.

(vi) *Error due to the mutual-inductance effect between the fixed and moving coils of the dynamometer.*—This error was shown to be negligible for the given dynamometer, exactly as in the case of the dynamometer used in the method dealt with in Section 6 (*g*)(iii).

(vii) *Error due to the grid current affecting the dynamometer reading.*—If the valve cannot be worked so that the grid potential is always negative, a current will flow in the grid coupling coil during part of each cycle and will alter the flux in the fixed coil of the dynamometer if this coil is used for coupling purposes with the grid.

Since the grid current will not flow during the whole cycle, the value of the nth harmonic in this current will be less than u/g of the nth harmonic in the anode current; where u = max. value of $\partial i_g/\partial v_g$, in which i_g = grid current, and $g = \partial i_a/\partial v_g$.

Now ratio of anode current to oscillatory current

= ratio of total admittance of two paths of oscillatory circuit to that of inductive path

$$= \frac{1/(r + jn\omega L) + jn\omega C}{1/(r + jn\omega L)}$$

$$= j\frac{r}{n\omega L} \text{ (approx.)}$$

It can also be shown that the ratio of flux densities produced at the centre of the fixed coil of the dynamo-

meter by the grid coupling coil and the fixed coil itself, respectively, is considerably less than

$$\frac{1}{10}\frac{\text{ampere-turns of coupling coil}}{\text{ampere-turns of fixed coil}}$$

for coils of the same relative dimensions as those used.

Thus the ratio of the flux density produced by the grid coupling to that due to the fixed coil is less than

$$\frac{ur \times 5\,000}{gn\omega L \times 10 \times 640}$$

In general, u/g will be less than $0 \cdot 2$; and so for $n = 3$, for which case it is greatest, the ratio of the two flux densities will be less than 1/30 for an r/L of 200 for the oscillatory circuit.

Since these flux densities differ in phase by approximately 90° the maximum value of the flux density in the fixed coil will only be increased by about $0 \cdot 06$ per cent, and so the error made in the maximum reading of the dynamometer due to this cause will in all cases be negligible.

(*f*) *Summary of errors.*—From the above discussion of the various sources of error it is seen that the only two important errors are due to the reading of the voltmeter across the coil being affected by the interfering harmonics, and to the impedance of the pressure coil differing from the reactance of the series condenser. The former error is only appreciable for the 3rd and 5th harmonics, while the latter only affects the highest harmonics. The former can be reduced by taking both sets of readings with the amplified oscillatory current for both 3rd and 5th harmonics, the amplification factor for the second set being about 25 per cent greater than for the first. By this means the error for the 3rd harmonic can easily be reduced to about $1 \cdot 5$ per cent of that harmonic. As already pointed out, the latter error can also be considerably reduced by redesigning the pressure-coil circuit. With these modifications the total theoretical error should not in any case exceed about 2 per cent of the harmonic being found, for an oscillatory circuit with a total ratio r/L of about 150.

The amplification that can be used with this method may have to be limited for the higher harmonics, if the variation in frequency of the supply being analysed is too great, owing to the corresponding variations that will occur in the magnitude and phase of the oscillatory current relative to the induced E.M.F.

The change in the dynamometer and voltmeter readings for a sudden change in frequency may be obtained as follows. Let the oscillatory circuit be tuned to the nth harmonic of the supply at its initial frequency $\omega/(2\pi)$, and let ϕ = change in phase of nth harmonic current relative to nth harmonic induced E.M.F. caused by a change in frequency given by $\delta\omega/\omega$. Then

$$\phi = \arc\tan\left[\frac{n(\omega+\delta\omega)L - 1/\{n(\omega+\delta\omega)C\}}{r}\right]$$

$$= \arc\tan\left[\frac{n^2\omega^2LC\{1+(2\delta\omega/\omega)+(\delta\omega/\omega)^2\}-1}{rn(\omega+\delta\omega)C}\right]$$

$$= \arc\tan\left(\frac{2n\omega L}{r}\cdot\frac{\delta\omega}{\omega}\right)\text{ (approx., since } n^2\omega^2LC = 1)$$

The oscillatory current and therefore the resonating voltage vary as $\cos\phi$, since impedance $= r/\cos\phi$ and r is fixed

$\therefore$ dynamometer reading varies as $\cos^2\phi$.

Therefore, if ϕ is small,

$$\frac{\text{change in dynamometer reading}}{\text{max. dynamometer reading}} = \sin^2\phi$$

$$= \left(\frac{2n\omega L}{r}\cdot\frac{\delta\omega}{\omega}\right)^2 \text{ approx.}$$

and

$$\frac{\text{change in voltmeter reading}}{\text{max. voltmeter reading}} = \frac{1}{2}\left(\frac{2n\omega L}{r}\cdot\frac{\delta\omega}{\omega}\right)^2 \text{ approx.}$$

Thus the likelihood of frequency variations affecting the readings will be greatest for the higher harmonics.

If actual $r/L = 200$ for $n = 23$, then a sudden change in frequency of $0 \cdot 2$ per cent for this harmonic will cause a change in phase $\phi = \arc\tan 0 \cdot 145$ which will cause decreases of approximately $2 \cdot 0$ per cent and $1 \cdot 0$ per cent in the readings of the dynamometer and voltmeter respectively. However, for an amplification factor of 8, which would mean an effective r''/L of 25, the same change of frequency would cause reductions of approximately 60 per cent and 35 per cent in the readings of the two instruments.

If this change of reading is a measure of the error, the latter can obviously be reduced by using a decreased amplification for the higher harmonics. The neon-lamp coupling could be increased to give a correspondingly larger reading for the unamplified current so that the error of reading is not increased. Thus, with an amplification factor of 2 for the 23rd harmonic the decrease in the dynamometer and voltmeter readings would be $7 \cdot 8$ per cent and $5 \cdot 0$ per cent respectively, for a change in frequency of $0 \cdot 2$ per cent. By using an amplification factor of only 2 an increase will be caused in some of the possible errors that have been dealt with, but it is not anticipated that the total error due to causes other than this fluctuation in frequency will exceed about $0 \cdot 07$ per cent of the fundamental.

It is difficult to predict theoretically the possible error that will arise from a fluctuation in supply frequency, since the latter will not in general be entirely periodic. Also the error will depend on the rate of change of frequency as well as on the limits of its variation. The only fluctuations that will be expected to cause an appreciable error will be those whose frequencies are of the same order as the natural frequency of the moving system of the dynamometer.

The effect of a comparatively high-frequency fluctuation which will naturally be small, will be to cause the dynamometer and voltmeter to give mean readings less than the true readings. Thus for a high-frequency variation in frequency, of amplitude $0 \cdot 1$ per cent, giving a total variation of $0 \cdot 2$ per cent, the maximum readings of the dynamometer and voltmeter that can be obtained will be less than the true maxima by $3 \cdot 9$ per cent and $2 \cdot 5$ per cent respectively for an amplification factor of 4, for the 23rd harmonic.

The fluctuations in speed of low-speed gas- or steam-

engine-driven alternators will be of this type, since the unbalanced torque causing the disturbance will have a frequency at least that of rotation of the crank shaft; this will not in general be less than about 5 per second.

For all very low-frequency variations and slow changes in frequency it will usually be possible to tune the oscillatory circuit so that the resonating current passes through its maximum value. Provided the change is not too rapid, the maximum values of the dynamometer and voltmeter readings will be the true values required.

For the tests performed it was not found necessary to reduce the amplification much for the higher harmonics, although some of the machines analysed were known to have very unsteady speeds. The limits of speed variation within which this method of analysis can be successfully employed were not found, but, as already pointed out, where the frequency fluctuation is large the effect of this fluctuation, which is greatest for the higher harmonics, can be considerably reduced by using less amplification.

(*g*) *Test-results.*—The effect of the valve in reducing the effective resistance of the oscillatory circuit is clearly shown in the oscillograms (Fig. 22) of the resonating voltage before and after amplification. These were obtained as before by connecting the element of the oscillograph direct to a small search coil, which was then brought near to the main inductance. These oscillograms show that the amplitude of the current is increased and that the damping factor as measured by the coefficient of decay of the oscillations is considerably reduced, the current being represented in each half-cycle by an equation of the form

$$i = e^{-rt/(2L)} A \sin n'\omega t$$

where n' differs very little from the order of the harmonic to which the circuit is tuned.

The results of an analysis obtained by this method of the line voltage of the three-phase Kolben alternator are given in Table 5.

In the following table v' and v'' are the voltages across the fixed coil of the dynamometer before and after amplification respectively, while d' and d'' are the corresponding maximum dynamometer deflections.

TABLE 5.

Analysis of Line Voltage of Three-phase Kolben Alternator at 34·5 cycles per second, 170 *volts.*

Order of harmonic n	Resonating voltage		Dynamometer deflection		Ratio of harmonic to fundamental
	v'	v''	d'	d''	
	volts	volts	cm	cm	per cent
3	3·5	10·0	0·95	0·8	0·11
5	2·85	14·3	2·6	15·0	5·46
7	5·3	21·5	1·4	2·5	0·35
9	2·6	15·4	0·6	0·4	0·08
11	9·4	26·0	− 0·5	1·4	0·57
13	4·1	12·6	4·95	15·45	6·35
15	2·5	15·0	0·0	0·4	0·16
17	2·5	18·2	1·4	4·3	0·22
19	2·6	17·5	0·4	6·4	0·51
21	2·4	18·0	− 0·2	0·37	0·43
23	6·4	22·0	2·95	10·4	2·40

The figures obtained for the analysis cannot be compared with the previous figures obtained for the same wave-form, as the machine was running under different conditions of excitation on the two occasions. However, although the absolute accuracy of the method was not verified, the above results show that harmonics known to be very small are in every case indicated as almost negligible, as in the case of the 3rd, 9th and 15th harmonics in the above wave-form. The results show that for these small harmonics the dynamometer reading is not increased appreciably when the analysing current is amplified, which indicates that in general no appreciable error is caused by the dynamometer reading being affected by the change in magnitude and phase of the

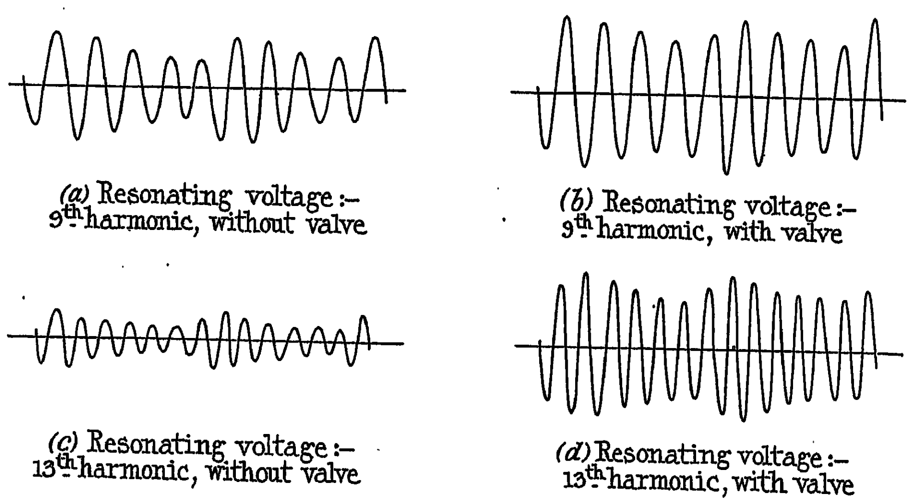

FIG. 22.—Oscillograms showing effect of amplification on the wave-form of the resonating voltage.

interfering harmonics in the analysing current due to the action of the valve, by the extra interfering harmonics induced in the oscillatory circuit by the valve, or by the current taken by the grid coupling of the valve. This is, of course, in accordance with the results of the theoretical investigation of these errors dealt with in Section 6. The average amplification of about 4 in the above results was obtained without difficulty.

In addition to the above test a special "sine wave" alternator was analysed. All the harmonics in the E.M.F. wave of this machine except the 3rd, 5th and 7th were found to be negligible, these latter being of the order of 0·5 per cent.

A test was also carried out on a 20-kW d.c. generator which had been converted into a two-phase alternator for iron-testing purposes. This was found to have a 4 per cent 3rd and a 0·9 per cent 5th harmonic, while all the other harmonics were less than 0·05 per cent.

8. The Possibility of Obtaining the Analysing Current from a Valve Generator without the Neon-Lamp Coupling.

(*a*) *General consideration.*—If the frequency of the wave-form to be analysed were absolutely constant it would be a simple matter to obtain the required analysing sinusoidal current from a valve generator, as the frequency of the latter can be adjusted to any desired value. With this method the oscillatory circuit would be so tuned that a beat period of several seconds was obtained with the harmonic being found, and thus with a suitably designed moving coil the maximum deflection of this would correspond to the instant when the two currents of the frequency of the desired harmonic are in phase, in which case the magnitude of the harmonic could be calculated from this deflection as before.

The time period of the beat must be at least three or four times the natural period of vibration of the moving coil, and so in carrying out the analysis of a 50-cycle wave to the 23rd harmonic this method would be limited to waves in which the maximum fluctuation in frequency did not exceed about 0·02 per cent of the fundamental frequency, or if the change in frequency were comparatively slow it might be limited to cases in which the rate of change of frequency did not exceed about 0·02 per cent per second.

In the neon-lamp method about 10 times this fluctuation can be allowed, and so it is seen that the application of the self-oscillatory method is limited in comparison with that of the neon-lamp method, which may be used in all cases except where the frequency is very unsteady. It will, however, be shown that in those cases in which the self-oscillatory method can be used it is much simpler and probably gives rather more accurate results than the neon-lamp method.

The chief considerations with regard to this method, as affecting the design of the circuits and possible errors, will now be briefly dealt with.

(*b*) *The circuit used and method of analysis.*—The valve circuit used in the last method can be employed, the connections being shown in Fig. 23, with the exception that the neon-lamp supply circuit is entirely dispensed with. The dynamometer can be essentially as before with a capacity in series with the pressure coil, while the resonating current can also be found as before from the voltage across the fixed coil of the dynamometer. Alternatively, the dynamometer and voltmeter may be replaced by a separate portable dynamometer and an ammeter, if this can be done without increasing too much the ratio r/L for the circuit. If an ammeter is used to measure the resonating current it will be advisable to replace the capacity in series with the pressure coil by a non-inductive resistance, so that the calculation of the harmonics does not involve an exact knowledge of the frequency.

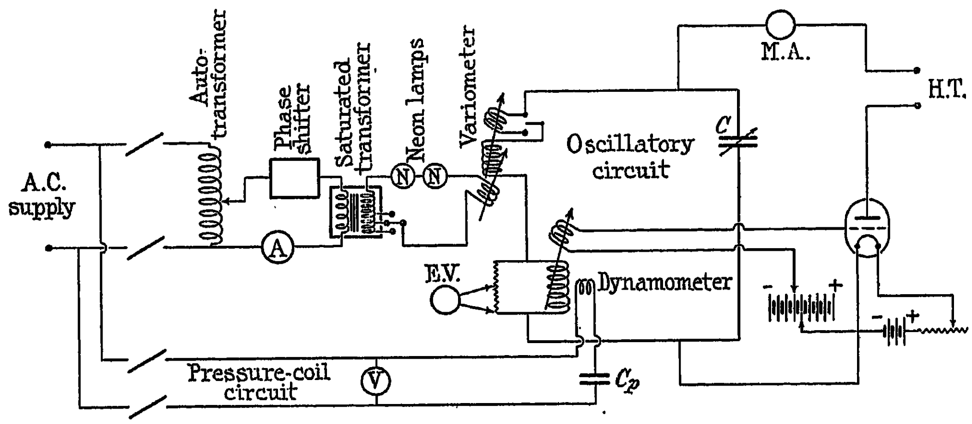

FIG. 23.—Circuit for complete method of analysis.
M.A. = d.c. milliammeter. E.V. = electrostatic voltmeter.

The very fine tuning essential for this method can be obtained by using a capacity variable in steps of 0·01 μF, and covering the intermediate range by means of a small variometer in series with the oscillatory circuit. This variometer must have a ratio of r/L comparable with that of the main inductance. An alternative method is to place a small piece of iron in the vicinity of the main inductance and alter the inductance by varying its position. This works quite well in practice.

To make a complete analysis of a wave-form, the capacity is set at approximately the amount required for the 3rd harmonic, and the circuit is then tuned until

a beat period of at least 4 or 5 seconds is obtained with this harmonic. The maximum reading of the dynamometer is taken, and also the corresponding readings of the voltmeter across the fixed coil of the dynamometer and voltmeter measuring the supply voltage. This is repeated for the other harmonics.

If the readings of the dynamometer and voltmeters are d_n, v_n and e, respectively, for the nth harmonic

then $d_n = ki_n i'_n$ (where k is the d.c. calibration constant)

$= ke_n n\omega C_p \frac{v_n}{n\omega L}$ (where e_n is the desired nth harmonic in E.M.F. wave)

$= k\frac{C_p}{L}e_n v_n$

Therefore $$e_n = \frac{L}{kC_p} \cdot \frac{d_n}{v_n}$$

from which the percentage of the harmonic [$= (100e_n/e)$ per cent] can be calculated.

From Fig. 24, which shows the relation between δ and β for various values of λ, it is seen that by making $\lambda = 0 \cdot 707$ the beat frequency can be as much as 40 per cent of the natural frequency of the moving system before the error exceeds 1 per cent of the reading. Thus for a natural period of 1 sec. for the moving system the beat period can be as small as $2 \cdot 5$ secs. without causing appreciable error.

The practical adjustment of the damping factor to the above figure will in general be a matter of trial and error. If oil damping is used the damping factor can be varied by adding oil of greater or less viscosity as required until the number of oscillations made before the amplitude falls to a given fraction of its initial value when a d.c. current through the coil is switched off, has the theoretical value.

(ii) *The error in the dynamometer reading due to the interfering harmonics in the oscillatory circuit.*—For a self-oscillatory circuit the saturation current of the valve is reached, and so, since the valve must be worked

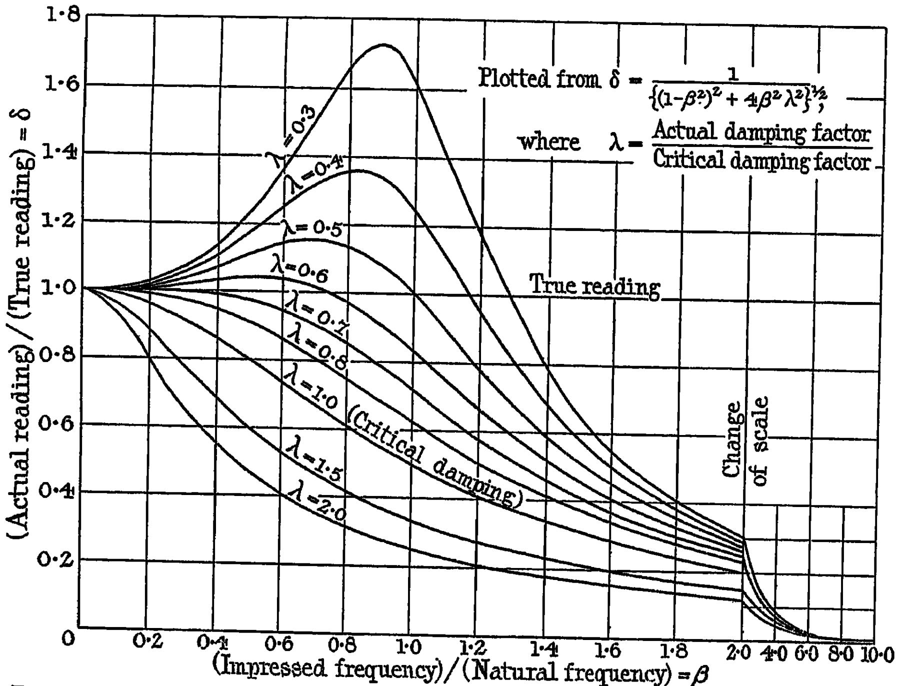

FIG. 24.—Curves showing effect of damping on maximum deflection of dynamometer.

(c) *The various sources of error.*

(i) *The error in the dynamometer reading due to the effects of inertia and damping on the moving system.*—This will be the chief source of error in this method of analysis, although it can be rendered inappreciable by a careful design of the moving system.

It is shown in Appendix 10 that

$$\frac{\text{actual max. reading}}{\text{true max. reading}} = \frac{1}{\sqrt{\{(1-\beta^2)^2 + 4\beta^2\lambda^2\}}} = \delta$$

where β = ratio of impressed to natural frequency of moving system,

and λ = ratio of actual damping factor to critical damping factor.

beyond the straight part of its characteristic, interfering harmonics are induced in the anode current and therefore in the oscillatory current. If the valve is worked from the middle of the characteristic the only appreciable harmonics will be those of odd orders.

It is shown in Appendix 11 that the only appreciable part of this error is due to the combined effect of all the pairs of harmonics of the same order in the currents in the two coils of the dynamometer. The maximum value of this error is shown to be less than $0 \cdot 0016 r/L$ per cent of the true reading, although the actual figure may be very much less than this, as it is unlikely that the deflections due to all the separate harmonics in the torque will have their maximum values at the same

instant that the true reading is a maximum. Also, the above error is for the analysis of a rectangular E.M.F. wave, for which it is considerably greater than for most E.M.F. waves likely to be analysed.

It thus appears that the ratio r/L of the oscillatory circuit might be made as large as 2 000 before the error is increased to 1 per cent of the reading. This would mean that a dynamometer and ammeter both of portable type could probably be employed, although it may not be advisable to replace the Moullin voltmeter by an ammeter, as the indication of the latter would have to be independent of frequency at the frequency of the higher harmonics.

(iii) *The error due to the voltmeter across the main inductance recording the R.M.S. value of the mixed wave and not the value of the resonating harmonic only.*

$$\text{Reading of voltmeter} = \frac{1}{\sqrt{2}}\sqrt{(V_n^2 + \Sigma V_{yn}^2)}$$

$$\text{Required value} = \frac{V_n}{\sqrt{2}}$$

$$\therefore \frac{\text{error}}{\text{reading}} = \frac{1}{2}\sum_{y=3}^{y=\infty}\left(\frac{V_{yn}}{V_n}\right)^2 \text{ approx.}$$

$$\text{But} \quad \frac{V_{yn}}{V_n} = \frac{I'_{yn}}{I'_n}\cdot\frac{yn\omega L}{n\omega L}$$

$$= \frac{r}{n\omega L(y^2-1)}$$

on substituting for I'_{yn}/I'_n from Equation (49) (Appendix 11).

$$\therefore \frac{\text{error}}{\text{reading}} = \frac{r^2}{2n^2\omega^2L^2}\sum_{y=3}^{y=\infty}\frac{1}{(y^2-1)^2}$$

$$< \frac{r^2}{2n^2\omega^2L^2}\left\{\frac{1}{64} + \frac{1}{2}\int_3^\infty \frac{d_y}{(y^2-1)^2}\right\}$$

$$< \frac{0{\cdot}012r^2}{n^2\omega^2L^2}$$

This error will be greatest for $n = 3$, for which case

$$\frac{\text{error}}{\text{reading}} < 1{\cdot}36 \times 10^{-3}\frac{r^2}{L^2}$$

Thus this error will not exceed 1 per cent of the reading if r/L for the oscillatory circuit is less than 860.

If an ammeter is used to measure the oscillatory current the error will be much less, as indicated in the last method of analysis.

(iv) *The error due to the resonating current being calculated from the reactance and not the impedance of the main inductance.*—This error can easily be shown to be

$$\frac{1}{2}\cdot\frac{r_1^2}{n^2\omega^2L_1^2} \text{ (approx.) of the harmonic being found.}$$

This error is greatest for the 3rd harmonic, and therefore for the error in this case not to exceed 1 per cent of the reading, the ratio r_1/L_1 for the main inductance must not exceed 130.

(v) *Error due to the reading of the voltmeter across the a.c. supply being taken as due to the fundamental only.*—This error is as dealt with for the previous method in Section 7(*e*)(iv), where it is shown to be negligible for all ordinary E.M.F. waves likely to be met with.

(vi) *Error due to the impedance of the pressure-coil circuit being taken as the reactance of the series condenser.*—This error is as dealt with for the previous method in Section 7(*e*)(v), where it is shown that it can be made sufficiently small by a suitable design of the pressure-coil circuit.

If an ammeter is used to measure the oscillatory current, and the capacity in series with the pressure coil is replaced by a non-inductive resistance, then the error made by taking the impedance of the pressure-coil circuit as its resistance is in general reduced to a negligible quantity.

(vii) *Error due to mutual-inductance effect between the fixed and moving coils of the dynamometer.*—This is as dealt with in Section 6(*g*)(iii). It will in general be possible to design a pressure coil so that the error due to this effect will not exceed 1 per cent of the reading when a series condenser is used.

(viii) *Error due to the grid current of the valve affecting the dynamometer reading.*—This error is shown to be inappreciable in Section 7(*e*)(vii).

9. Conclusions.

Where the frequency of the a.c. supply being analysed is sufficiently steady to permit its use, the self-oscillatory method has been shown to be capable of giving very accurate results. As the ratio r/L for the oscillatory circuit can be made as large as 1 000 without the error exceeding about 2 per cent of the harmonic being found for the larger harmonics, the whole apparatus can be made very compact and only portable instruments need be employed.

As this method cannot be of general application, however, owing to the limit imposed by frequency variations, the most useful method to meet general requirements will be a combination of this method with the neon-lamp method. The valve used will in the one case supply the necessary oscillatory current, and in the other amplify the current induced by the neon-lamp circuit. This combination of the two methods can be very simply effected, since it is only necessary to modify the apparatus of the neon-lamp method with valve amplification to the extent of ensuring that the damping of the moving system of the dynamometer is properly adjusted, and to provide means of that very fine tuning which is essential to the self-oscillatory method.

The latter feature can be arranged for by using a variometer for the final stage of the tuning, this consisting of a small coil connected in series with the main inductance used for the neon-lamp coupling, and capable of being rotated in it at the opposite end to the coil carrying the neon-lamp current.

The ratio r/L for the oscillatory circuit cannot be as large as for the self-oscillatory method alone, as the requirements of the neon-lamp method will limit it to between 150 and 200. For this figure it should be possible to analyse E.M.F. waves to within 2 per cent of the harmonic itself when using the neon-lamp method, and to within less than 1 per cent of the harmonic itself when

using the self-oscillatory form of apparatus. If the harmonics to be found are small, the accuracy will, of course, be limited by the experimental error in reading the dynamometer.

An attempt should always be made to carry out the analysis with the self-oscillatory method, owing to its greater simplicity and accuracy, but if the fluctuations in frequency are too great then the neon-lamp method can be used.

The complete diagram of connections has already been given in Fig. 23, and the chief features of the complete apparatus required are outlined below.

Neon-lamp circuit.

Auto-transformer. This takes about 2 amperes from the a.c. supply.

Phase-shifter. This should if possible be of a type which requires only one adjustment to be made. If a choke coil is used the iron circuit of this should be closed, so that the external field produced is small. Failing this it may be necessary to enclose it in a thin sheet-iron box for screening purposes so that the dynamometer is not affected.

Ammeter. Ordinary commercial type.

Saturated transformer. This should have 3 tappings on the secondary for use with frequencies of 25, 50 and 100, respectively.

Neon lamps. Two of these only will be required, connected "back to back."

Coupling with oscillatory circuit. Coil of about 1 000 turns that can be rotated inside one end of the smaller inductance of the oscillatory circuit.

To ensure that the desired E.M.F. wave is always induced in the oscillatory circuit, the primary current of the saturated transformer is always adjusted to have a specified value by means of tappings on the auto-transformer across the a.c. supply.

Oscillatory circuit.

Capacity. This should give ranges from $0 \cdot 5$ μF to $10 \cdot 0$ μF in steps of $0 \cdot 5$ μF, and from $0 \cdot 01$ μF to $0 \cdot 5$ μF in steps of $0 \cdot 01$ μF. These two ranges can be controlled by two dial switches, and will provide sufficiently fine tuning for the neon-lamp method.

Main inductance. This is also the fixed coil of dynamometer. It can be designed to have a ratio $r/L = 75$ and to give 4 ranges of inductance with plug connections. The external diameter of such a coil would be about 25 cm.

Dynamometer pressure coil. This is suspended inside the main inductance. The pressure coil and the condenser used in series with it must be so designed that the error due to the mutual-inductance effect, and that due to the impedance of the circuit being taken as the reactance of the series condenser, are both sufficiently small for the higher harmonics. The damping factor must be adjusted to be $0 \cdot 71$ of the critical damping factor. The deflection is most conveniently observed by reflecting a spot of light on a scale at a distance of about 1 m from the coil.

Voltmeter across a.c. supply. This can be a portable instrument of the ordinary commercial type.

Voltmeter across fixed coil of dynamometer. The most suitable instrument is a Moullin thermionic valve voltmeter, in conjunction with a suitable series resistance.

Coupling with neon-lamp circuit. The coil used for this purpose can be much smaller than the main inductance coil. It can be so designed that $L_2 = \frac{1}{4}L_1$ and $r_2/L_2 = 200$, so that the contribution to the total r/L of the oscillatory circuit by the two inductance coils will be 100. This coil should also have 4 ranges of inductance as for the main coil. Its external diameter would be about 18 cm.

Fine-tuning variometer. This should consist of a coil which can be rotated in the above coil, at the opposite end to the neon-lamp current coupling coil. It will require to be wound with about 1/30th of the number of turns in series on the above coil for the largest range of inductance. This will give a total variation in frequency corresponding to a change in capacity of $2 \cdot 0$ per cent on the greatest or first range of inductance, 8 per cent on the second and 10 per cent on the third. This variometer coil can, by changing a plug connection, be connected in series with the coil in which it rotates. It will increase the r/L of the oscillatory circuit by about 10, 40 and 100 respectively, for the three ranges of inductance, but as already shown this will not affect the accuracy of the self-oscillatory method for which method alone it is used.

It may be advisable to screen the dynamometer from the above combination of coils by the use of a thin sheet-iron container round the latter.

Valve circuit.

Three-electrode valve. This must be of a standard type with a saturation current of not less than about 40 mA.

Grid coupling. A coil that can be rotated at one end of the fixed coil of the dynamometer.

Filament d.c. voltmeter. Commercial type.

Low-tension supply for filament. 6-volt accumulator.

Filament rheostat.

Grid potential battery. Dry battery in steps of 3 volts up to about 36 volts.

High-tension supply for anode circuit. In most cases a 400-volt d.c. supply will be available. This is preferable but, failing it, a 200-volt supply will suffice.

D.C. milliammeter in anode circuit. This is not absolutely essential, although its indications are very useful.

In conclusion a list will now be given of the necessary operations to be carried out for the complete analysis of an E.M.F. wave-form.

Procedure to be followed for the analysis of an E.M.F. wave-form.

Preliminary.

Connect high-voltage d.c. supply in anode circuit.

Connect a.c. supply to be analysed to terminals of apparatus.

Adjust filament voltage to normal value.

Adjust grid voltage to give mid-point of characteristic, when milliammeter will record one-half the saturation current.

The self-oscillatory method.

Connect inductance coils of oscillatory circuit to give maximum range.

Connect fine-tuning variometer in series with circuit by changing plug connection.

Set capacity at approximate value required for 3rd harmonic as read from graph.

Increase grid coupling until circuit oscillates.

Tune circuit until period of beat with 3rd harmonic is greater than 3 secs., and preferably as large as possible.

Observe (i) maximum deflection of dynamometer, d.
(ii) corresponding resonating voltage, v.
(iii) corresponding supply voltage, e.

Repeat for higher harmonics in order, changing inductance to a lower range when capacity is reduced to about 1 μF.

Calculate each harmonic $= Kd/(ev) \times 100$ per cent of fundamental, where $K =$ constant for given range of inductance used.

If the fluctuation in frequency is too great for steady readings to be obtained with the self-oscillatory method, then use the neon-lamp method as follows:—

The neon-lamp method.

Connect neon-lamp circuit to appropriate tapping on secondary of saturated transformer according to frequency of a.c. supply.

Adjust auto-transformer to give specified current through primary of saturated transformer.

Disconnect fine-tuning variometer from oscillatory circuit.

Connect inductance coils to give maximum range.

Set capacity at approximate value required for 3rd harmonic.

Tune circuit to 3rd harmonic.

Adjust neon-lamp coupling to give a resonating voltage within the specified limits.

Switch off neon-lamp supply.

Switch on filament supply to valve.

Adjust grid coupling so that the circuit is almost but not quite self-oscillatory.

Switch on neon-lamp supply.

Retune oscillatory circuit.

Readjust grid coupling to give amplification of about 6.

Adjust phase-shifter to give maximum dynamometer reading.

Take readings of—
(i) maximum dynamometer deflection, d'.
(ii) resonating voltage, v'.
(iii) a.c. supply voltage, e'.

Readjust grid coupling to increase amplification further by about 25 per cent.

Retune and readjust phase if necessary.

Take readings of instruments as before, d'', v'' and e'' respectively.

Repeat above operations for the 5th harmonic. Above the 5th harmonic, the first set of readings can be taken before the oscillatory current is amplified, the phase-shifter being first adjusted to give a maximum dynamometer reading. In this case only one set of readings is necessary with the amplified current. In each case,

$$\text{harmonic} = K\frac{(d''/e'') - (d'/e')}{v'' - v'} \times 100 \text{ per cent of the}$$

fundamental, where $K =$ same constant as for the self-oscillatory method.

Finally, although only the case of the analysis of E.M.F. waves has been discussed in the paper, the method advocated can obviously be applied to the analysis of all forms of periodic voltage and current waves, since it is always possible to pass through the moving coil of the dynamometer a current whose harmonics bear a known relation to those of the wave-form in question.

The authors are greatly indebted to Mr. C. P. Lockton, who did much useful experimental work in the later stages, and to Messrs. Metropolitan-Vickers Electrical Co., Ltd., for the manufacture of the inductance coils and for the loan of apparatus.

APPENDIX 1.

To Find I'_n/I'_x and V_n/V_x for Circuit 1.

Circuit 1.—The circuit has already been given in Fig. 1.

Let $L, r_1 =$ self-induction and resistance of choke coil.

$C =$ capacity of condenser.

R_1 and $R =$ non-inductive resistances of the order of 50 000 ohms and 200 000 ohms respectively.

$$e = \sum_1^\infty E_n \sin n\omega t = \text{E.M.F. applied to AB.}$$

$$v = \sum_1^\infty V_n \sin (n\omega t - \phi_n) = \text{E.M.F. across DE.}$$

$i_t =$ current in AD.

$$i = \sum_1^\infty I'_n \sin (n\omega t - \phi'_n) = \text{current in choke coil.}$$

$i_c =$ current in condenser.

$i_r =$ current in R.

Consider the effect of one harmonic of E.M.F. alone. Treating symbolically we obtain

$$i_t = V_n\left[\frac{1}{r_1 + jn\omega L} + jn\omega C + \frac{1}{R}\right]$$

$$= V_n\left[\frac{1}{R} + \frac{1 - n^2\omega^2LC + jr_1n\omega C}{r_1 + jn\omega L}\right]$$

and $$E_n = R_1 i_t + V_n$$

$$\therefore V_n = E_n\Big/\left[1 + R_1\left\{\frac{1}{R} + \frac{1 - n^2\omega^2LC + jr_1n\omega C}{r_1 + jn\omega L}\right\}\right] \quad (7)$$

If now we tune the circuit to the frequency of the nth harmonic, i.e. make $n^2\omega^2LC = 1$, we have

$$V_n = E_n\Big/\left[1 + R_1\left\{\frac{1}{R} + \frac{r_1C}{L}\right\}\right] \text{neglecting } r_1 \text{ in comparison with } n\omega L$$

$$= E_n\Big/\left[1 + \frac{R_1rC}{L}\right] \quad \ldots \ldots \quad (8)$$

where $$r = r_1 + \frac{L}{CR}.$$

We have also

$$\frac{V_n}{V_x} = \frac{E_n}{E_x} \cdot \frac{1 + R_1[(1/R) + (1 - x^2\omega^2LC + jxr_1\omega C)/(r_1 + jx\omega L)]}{1 + (R_1 rC/L)}$$
$$= \frac{E_n}{E_x} \cdot \frac{1 + R_1[\{(1/R) + r_1C/L\} - jR_1(1 - x^2/n^2)/x\omega L]}{1 + (R_1 rC/L)}$$

to same order of approximation and since $x^2\omega^2LC = x^2/n^2$. Thus

$$\frac{V_n}{V_x} = \frac{E_n}{E_x} \cdot \frac{1 + (R_1 rC/L) - (jR_1\omega C)\,(n^2 - x^2)/x}{1 + (R_1 rC/L)}$$
$$= \frac{E_n}{E_x}\left[1 - j\frac{n^2 - x^2}{x} \cdot \frac{R_1\omega C}{1 + (R_1 rC/L)}\right] \quad . \quad . \quad (9)$$
$$= -j\frac{E_n}{E_x} \cdot \frac{n^2 - x^2}{x} \cdot \frac{R_1\omega C}{1 + (R_1 rC/L)} \text{ (approx.)} \quad (10)$$

since in general the real part will be small compared with the imaginary part.

Now $$I'_n = \frac{V_n}{r_1 + jn\omega L} = \frac{V_n}{jn\omega L} \text{ (approx.)}$$
so that

$$\frac{I'_n}{I'_x} = -j\frac{E_n}{E_x} \cdot \frac{n^2 - x^2}{x} \cdot \frac{x}{n} \cdot \frac{R_1\omega C}{1 + (R_1 rC/L)}$$
$$= -j\frac{E_n}{E_x} \cdot \frac{n^2 - x^2}{n} \cdot \frac{R_1\omega C}{1 + (R_1 rC/L)} \quad . \quad . \quad (11)$$

As R_1Cr/L becomes large compared with unity, we have as a further approximation

$$\frac{I'_n}{I'_x} = -j\frac{E_n}{E_x} \cdot \frac{n^2 - x^2}{n} \cdot \frac{\omega L}{r} \quad . \quad . \quad . \quad (12)$$

and $$\frac{|I'_n|}{|I'_x|} = \frac{E_n}{E_x} \cdot \frac{n^2 - x^2}{n} \cdot \frac{\omega L}{r}.$$

We are chiefly concerned with the ratios of the amplitudes and not with the phases of the various quantities.

APPENDIX 2.

The Probable Error Introduced by an Imperfect Auxiliary Wave.

Standard method.—We have, from Section 5(*b*),

$$\psi = \sum_{x=3}^{x=\infty} \frac{I_{xn}}{I_1} \frac{I'_{xn}}{I'_n} \cos \theta_{xn}$$

and from Equation (11),

$$\frac{I'_{xn}}{I'_n} \leqslant \frac{E_{xn}}{E_n} \cdot \frac{n}{n^2x^2 - n^2} \cdot \frac{r}{\omega L} \cdot \frac{1 + (R_1 rC/L)}{R_1 rC/L}$$
$$\leqslant \frac{4}{3} \cdot \frac{E_{xn}}{E_n} \cdot \frac{n}{n^2x^2 - n^2} \cdot \frac{r}{\omega L},$$

provided we make R_1 sufficiently great.

Also from Equation (5*a*), using the first commutator,

$$\frac{E_{xn}}{E_n} \leqslant \frac{1}{x}$$

so that $$\frac{I'_{xn}}{I'_n} \leqslant \frac{4}{3} \cdot \frac{r}{n\omega L} \cdot \frac{1}{x(x^2 - 1)}$$

$$\therefore \psi \leqslant \sum_{x=3}^{x=\infty} \frac{I_{xn}}{I_1} \cdot \frac{4}{3} \cdot \frac{r}{n\omega L} \cdot \frac{1}{x(x^2 - 1)}$$
$$\leqslant \frac{4}{3}\frac{r}{n\omega L}\left[\frac{I_{xn}}{I_1}\right]_{max.} \sum_{x=3}^{x=\infty} \frac{1}{x(x^2 - 1)}.$$

Since the summation is for odd values of x only,

$$\psi \leqslant \frac{1}{15n}\left[\frac{I_{xn}}{I_1}\right]_{max.} \frac{3}{8}\left\{\frac{\pi^2}{8} - 1\right\}$$

and substituting $r/L = 15$, $\omega = 314$, and since also $n \geqslant 3$ in all cases,

$$\psi \leqslant \frac{1}{500}\left[\frac{I_{xn}}{I_1}\right]_{max.} \quad . \quad . \quad . \quad . \quad (13)$$

APPENDIX 3.

Design of Fixed Coil.

The conditions to be fulfilled in the design of the fixed-coil system are :—

(1) The ratio r_1/L must be not greater than some fixed figure when measured with direct current.
(2) The ratio of effective resistance to the resistance measured with direct current must be as small as possible at 1 000 cycles per second, i.e. the eddy-current loss must be small.
(3) It must be possible to obtain values of self-induction as low as 0·005 henry when all the layers are connected in parallel.

Maxwell's approximate formula for the self-induction of a coil of rectangular section is

$$L = 4\pi n^2 a\left(\log_e \frac{8a}{R} - 2\right) \times 10^{-9} \text{ henry} \quad . \quad (15)$$

where n = number of turns,
a = mean radius of coil,
and R = geometric mean distance of the transverse section of the coil from itself.

If the section be $(b \times c)$cm², then

$$R = 0{\cdot}2235(b + c) \text{ approx.} \quad . \quad . \quad (16)$$

Maxwell shows that the coil of maximum self-induction for a given length of wire, and therefore for a given resistance, is given by

$$\log_e \frac{8a}{R} = \frac{7}{2}$$

or $a = 0{\cdot}921\ (b + c)$ on substitution from Equation (16) . (17)

Then Equation (15) becomes

$$L = 6\pi n^2 a \times 10^{-9} \text{ henry}.$$

Now the resistance of the coil to direct current is given by

$$r_1 = \frac{2\pi a n \times 1\cdot 7 \times 10^{-6}}{\text{wire section}} \text{ ohm}$$

and $n \times$ (wire section) $= bc \times \alpha$, where α is the space factor.

Hence $$r_1 = \frac{2\pi a n^2 \times 1\cdot 7 \times 10^{-6}}{bc \times \alpha}$$

so that $$\frac{L}{r_1} = \frac{3\,bc\alpha \times 10^{-9}}{1\cdot 7 \times 10^{-6}} = 1\cdot 77\,bc\alpha \times 10^{-3}.$$

Thus, since $bc\alpha$ is the net copper section, it is clear that if the coil be made according to Maxwell's rule the ratio L/r_1 varies directly as the copper section and therefore depends only on the weight of copper put into the coil.

The weight of copper required varies as $a \times bc \times \alpha$, i.e. as $bc(b + c)$ from Equation (17).

Hence, since bc is fixed by the ratio L/r_1, it is clear that the most economical coil is one with a square section if we have only to consider the d.c. resistance. Since, however, the eddy-current loss will depend on the shape of the coil for a given number of ampere-turns in the coil, we have to consider the effect of varying the ratio of axial length to winding depth, i.e. b/c.

We have to consider the eddy-current loss at frequencies of the order of 1 000. It is clear in the first place that the skin effect will be negligible at these frequencies, and that we can therefore calculate the eddy-current loss in the wire by the formula given by Howe:*

$$W_e = \frac{\pi^2}{8} B^2 f^2 \times d^2 \times \frac{10^{-16}}{\rho} \text{ watt/cm}^3$$

where f is the frequency, d the diameter of wire, ρ the specific resistance in ohms, and B the maximum value of the flux density at the point considered.

B can be found approximately from the dimensions of the coil for a given number of ampere-turns in the coil, and it is clear that if this number be fixed the average value of B will decrease as the coil is lengthened axially. Thus the eddy-current loss will decrease with c/b; on the other hand for a fixed volume of copper, on changing the dimensions to conform to Maxwell's rule, the ratio L/r_1 will decrease. There is thus a definite ratio of c/b which will give a minimum loss for a particular frequency. This may be obtained by a process of trial and error. In the first coil constructed c/b was made equal to 0·25 and the calculated ratio of eddy-current loss to direct-current loss was 0·45 at 1 100 cycles per second.

A further factor to be considered is the distribution of current amongst the various layers when they are connected in parallel. To avoid extra loss we have clearly to arrange for equal distribution of current. This will obtain approximately if the mutual inductance between any *one layer* and the rest of the coil is constant for the various layers. This can be arranged by reducing the number of turns per layer as the diameter of the coil increases. The calculation to determine the exact number of turns is rather laborious and only the outline of the method of calculation will be given.

The mutual inductance between any layer and the rest of the coil may be obtained by summing the values of mutual inductance between this layer and each of the other layers. Maxwell's formula for the mutual inductance of two coaxial solenoids of radii c_1, c_2 and length l is

$$M = 4\pi n_1 n_2 c_2^2 (l - 2c_1 d)$$

where $$d = \frac{1}{2}\frac{(c_1 + l - r)}{c_1} - \frac{1}{16}\frac{c_2^2}{c_1^2}\left(1 - \frac{c_1^3}{r_3}\right) + \cdots$$

where $r = \sqrt{(l_1^2 + c_1^2)}$ and n_1, n_2 are the numbers of turns in the two coils. M may be calculated for c_1 fixed and various values of c_2 corresponding to several layers throughout the coil, assuming equal numbers of turns. A few values only need be calculated; the remainder can be obtained by interpolation. By the use of a graphical method the summation for the total mutual inductance can then be easily carried out. This is repeated for other values of c_1 and then by interpolation the mutual inductance between the whole coil and any layer may be found. It will appear that

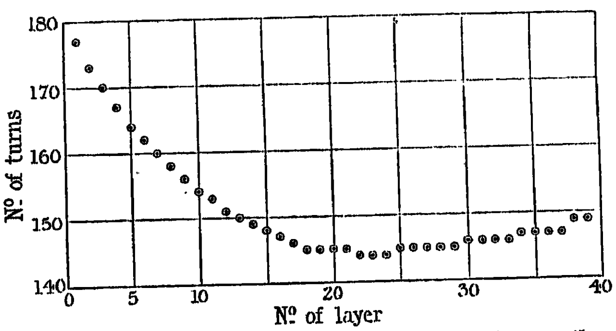

FIG. 25.—Turns per layer on dynamometer fixed coil.

for an equal number of turns in each layer the mutual inductance increases by about 20 per cent in passing from the inner layers to the centre, and then decreases slightly for the outer layers. The corrected number of turns for each layer to make these mutual inductances equal is then found. This gives a first approximation to the correct number of turns. Using these new figures for the turns per layer the calculation should be repeated to get a closer approximation, since the relative contribution of the outer layers of the coil will be reduced. This correction can be effected quite simply graphically and the second approximation should give close enough results in practice.

This method of calculation was adopted for both types of coils constructed, and the figures showing the variation in the turns per layer are given in Fig. 25 for the second coil.

Details of dynamometer used with methods 3 and 4.

(i) *Fixed coil.*

Mean radius: 11·7 cm.
Axial length: 7·7 cm.
Winding depth: 2·35 cm.

* *Proceedings of the Royal Society*, A, 1916-17, vol. 93, p. 468.

Turns per layer: 177 for inner layer, varying uniformly to 145 for centre layer and 148 for outer layer.
No. of layers: 40.
Wire: No. 26 S.W.G.
Self-induction—all layers in parallel: 0·0058 henry.
Resistance—all layers in parallel: 0·314 ohm.
Ratio r_1/L with direct current: 54.

(ii) *Moving coil.*
Winding: 450 turns of No. 32 S.W.G. wire.
Resistance: 140 ohms.
Self-induction: 0·016 henry.
Period: 2 secs.
Weight: 35 g.
Dimensions: $15 \times 1\cdot5 \times 1\cdot0$ cm³.
Suspension: bifilar.

APPENDIX 4.

Consideration of Possible Sources of Error in the Readings of the Instruments.

(i) *Reading of the electrostatic voltmeter.*—The torque on the moving system of the electrostatic voltmeter is proportional to the sum of the squares of the amplitudes of the various harmonics of E.M.F. across the oscillatory circuit. Thus the deflection d on a uniform scale is given by

$$d = K(V_1^2 + V_3^2 + \ldots V_n^2 + \ldots)$$

Thus the computed value V_n of the resonating voltage from this deflection will be

$$V_n' = V_n\left[1 + \left(\frac{V_1}{V_n}\right)^2 + \left(\frac{V_3}{V_n}\right)^2 + \ldots \left(\frac{V_x}{V_n}\right)^2 + \ldots\right]^{\frac{1}{2}}$$

The proportional error is given by

$$\frac{V_n' - V_n}{V_n} = \delta$$

and $$\delta = \left[1 + \left(\frac{V_1}{V_n}\right)^2 + \left(\frac{V_3}{V_n}\right)^2 + \ldots\right]^{\frac{1}{2}} - 1 \quad . \quad (18)$$

For the standard method all the values of V_x except for $V_{(2r+1)n}$ are zero, and

$$\frac{V_{xn}}{V_n} \leqslant \frac{E_{xn}}{E_n}\cdot\frac{r}{\omega L}\cdot\frac{xn}{n^2 - n^2x^2}\cdot\frac{4}{3} \text{ [from Equation (12)]}$$
$$\leqslant \frac{4}{3}\cdot\frac{r}{n\omega L}\cdot\frac{1}{1 - x^2}$$

Thus

$$\delta \leqslant \left[1 + \frac{16}{9}\cdot\frac{r^2}{n^2\omega^2L^2}\sum_{r=1}^{r=\infty}\left\{\frac{1}{1 - (2r+1)^2}\right\}^2\right]^{\frac{1}{2}} - 1$$

and for $r/L = 15$ and $\omega = 314$,

$$\delta \leqslant \left[1 + \frac{1}{5\,000n^2}\right]^{\frac{1}{2}} - 1 = \frac{1}{10^4n^2} \text{ (approx.)}$$

δ is thus negligible for all values of n.

(ii) *The effect of the mutual induction between fixed and moving coil circuits.*—We have to calculate the E.M.F. induced in the moving coil by the fixed-coil flux for a given angular position of the former.

Let $(\frac{1}{2}\pi + \theta)$ be the angle between the magnetic axes of the fixed and moving coils; A the effective area of the moving coil; R, L, the resistance and self-induction of the moving-coil circuit; n the number of turns in the moving coil and H the amplitude of the magnetic force due to the fixed coil.

Then it may easily be shown that the torque due to mutual induction is

$$\frac{1}{4}(AHn)^2\frac{\omega^2L}{R^2 + \omega^2L^2}\sin 2\theta \times 10^{-9} \text{ dyne-cm.}$$

If we substitute

$H = 15\sqrt{2}$, $\omega = 1\,150 \times 6\cdot28$, $n = 200$,
$L = 6 \times 10^{-3}$ henry, $R = 1\,000$ ohms, $A = 24$ cm²,
mean torque $= 0\cdot7 \sin 2\theta$ dyne-cm.

The maximum value of $\sin 2\theta$ with the scale used was 0·25. The torque due to a 1 per cent harmonic with the same value of H is 7·2 dyne-cm.

Thus the torque due to mutual induction is 2·4 per cent of the deflection due to a 1 per cent harmonic. The error due to this will be negligible.

(iii) *The effect on the constant of the instrument of a variation with frequency of the distribution of current in the fixed coil.*—This point was tested experimentally by changing the distribution of a constant direct current in the fixed coil whilst keeping a constant direct current in the moving coil. The maximum variation in the constant was so small as to be negligible.

APPENDIX 5.

To Find the Maximum Error in the Dynamometer Reading Due to all Harmonics of Order Greater than x_0.

We require the closest possible approximation to

$$\frac{r}{\omega L}\sum_{x=x_0+2}^{x=\infty}\frac{I_x}{I_1}\cdot\frac{E_x}{E_n}\cdot\frac{x}{x^2 - n^2}$$

as an upper limit.

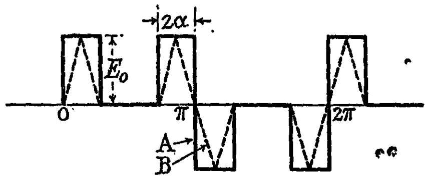

Fig. 26.—Limiting forms of the E.M.F. wave induced in the oscillatory circuit.

For most wave-forms likely to be analysed we shall have

$$\frac{I_x}{I_1} \leqslant \frac{1}{x}$$

The actual wave-form of the E.M.F. induced in the oscillatory circuit is intermediate between the wave-forms A and B in Fig. 26 and so we may expect its

harmonics to be intermediate between the corresponding harmonics in A and B.

The xth harmonic in A is

$$A_x = \frac{8E_0}{\pi} \cdot \frac{\sin^2 xa}{x}$$

and the xth harmonic in B is

$$B_x = \frac{8E_0}{\pi} \cdot \frac{\sin xa(1 - \cos xa)}{x^2 a}$$

$$|A_x| = \left|\frac{8E_0}{\pi} \cdot \frac{\sin^2 xa}{x}\right|$$

$$\leqslant \frac{8E_0}{\pi} \cdot \frac{1}{x} \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

Also $$|B_x| = \left|\frac{8E_0}{\pi} \cdot \frac{\sin xa(1 - \cos xa)}{x^2 a}\right|$$

$$\leqslant \left|\frac{8E_0}{\pi} \cdot \frac{1}{x} \cdot \frac{1 - \cos xa}{xa}\right|$$

But for the maximum value of $\frac{1 - \cos xa}{xa}$ we have $xa^2 \sin xa - a(1 - \cos xa) = 0$, that is $(1 - \cos xa) = xa \sin xa$.

$$\therefore |B_x| \leqslant \left|\frac{8E_0}{\pi} \cdot \frac{1}{x} \cdot \frac{xa \sin xa}{xa}\right|$$

$$\leqslant \frac{8E_0}{\pi} \cdot \frac{1}{x} \cdot \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

But $|E_x|$ is less than the greater of $|A_x|$ and $|B_x|$

$$\therefore |E_x| \leqslant \frac{8E_0}{\pi} \cdot \frac{1}{x} \cdot \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

Also $|B_n| \leqslant |A_n|$ for all integral values of $n \leqslant n_0$ where n_0 is given by

$$1 - \cos n_0 a = n_0 a \sin n_0 a$$

from which $\quad n_0 a = 2 \cdot 32$ radians (approx.) $= 133°$

The most suitable E.M.F. wave for induction in the oscillatory circuit is one for which $a = 6°$ (approx.), for which the maximum harmonic is about the 11th or 13th.

For $a = 6°$, $n_0 = 22 \cdot 1$ and we shall make no appreciable error in taking $|E_n| \geqslant |B_n|$ providing we do not require n to be greater than 23.

Using the above inequalities we have

Max. error due to terms of order $> x_0$

$$\psi_2 = \frac{r}{\omega L} \sum_{x=x_0+2}^{x=\infty} \frac{I_x}{I_1} \cdot \frac{E_x}{E_n} \cdot \frac{x}{x^2 - n^2}$$

$$= \frac{r}{\omega L} \cdot \frac{n^2 a}{\sin na(1 - \cos na)} \sum_{x=x_0+2}^{x=\infty} \frac{1}{x(x^2 - n^2)}$$

Since $x_0 > n$, $1/\{x(x^2 - n^2)\}$ is positive and decreasing through the whole range of x given by $x_0 + 2 \leqslant x \leqslant \infty$

$$\therefore \psi_2 \leqslant \frac{r}{\omega L} \cdot \frac{n^2 a}{\sin na(1 - \cos na)} \frac{1}{2} \int_{x_0}^{\infty} \frac{dx}{x(x^2 - n^2)}$$

$$= \frac{r}{\omega L} \cdot \frac{n^2 a}{2 \sin na(1 - \cos na)} \cdot \frac{1}{2n^2} \log_e \frac{x_0^2}{x_0^2 - n^2}$$

$$< \frac{r}{\omega L} \cdot \frac{0 \cdot 577a}{\sin na(1 - \cos na)} \log_{10} \frac{1}{1 - (n/x_0)^2} \quad . \quad (21)$$

APPENDIX 6.

To Find I_n''/I_x'' for the Given Combination of Oscillatory and Valve Circuits.

The directions taken as positive in the various parts of the circuit shown in Fig. 27 are indicated by arrows. At each mutual inductance the separate inductances must be so arranged that a positive current in each circuit produces a flux in the same direction.

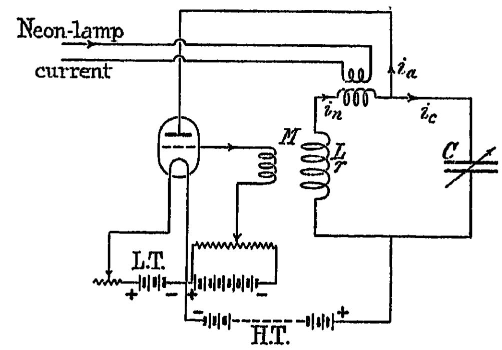

Fig. 27.—Valve circuit used to amplify resonating current.

Considering one harmonic only and making use of the operator D for d/dt, we have

e_n = E.M.F. of nth harmonic induced in oscillatory circuit by neon-lamp current

$$= E_n \sin n\omega t$$

$$= LDi_n + ri_n + \frac{1}{C}\int i_c dt \,. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

where i_n = current of nth harmonic through main inductance

$$= I_n'' \sin (n\omega t - \phi_n')$$

From (22) $e_n = (LD + r)i_n + \dfrac{i_c}{CD}$ (since with the notation employed $\int i_c dt$ may be replaced by $\dfrac{1}{D} i_c$)

$$= \left(LD + r + \frac{1}{CD}\right)i_n - \frac{i_a}{CD} \quad . \quad . \quad (23)$$

since $\quad i_c = i_n - i_a$

For the valve we have, with the notation of Section 7(*b*),

$$Di_a = aDv_a + gDv_g$$
$$= aD(\text{const.} - (LD + r)i_n + e_n) + gD(\text{const.} + MDi_n)$$
$$= \{(gM - aL)D^2 - arD\}i_n + aDe_n$$
$$\therefore i_a = \{(gM - aL)D - ar\}i_n + ae_n$$

and substituting for i_a in (23) we have

$$\left(1 + \frac{a}{CD}\right)e_n = \left\{LD + \left(r - \frac{gM - aL}{C}\right) + \frac{1 + ar}{CD}\right\}i_n \quad (24)$$

To find the particular integral of this differential equation which corresponds to the final steady conditions, we may replace D in it by $jn\omega$, the result then being given in symbolic notation. Thus

$$e_n = \left\{r - \frac{gM - aL}{C} + j\left(n\omega L - \frac{1 + ar}{n\omega C}\right)\right\}i_n \text{ (approx.)} \quad (25)$$

since $a/(Cn\omega)$ is negligible compared with 1.

The effective resistance is at once seen to be, $r'' = r - (gM - aL)/C$ which, being independent of frequency, is the same for all the harmonics.

For maximum current the oscillatory circuit is tuned so that $n^2\omega^2LC = 1 + ar$, when Equation (25) reduces to

$$i_n = \frac{e_n}{r - (gM - aL)/C} \quad . \quad . \quad . \quad (26)$$

Again, considering the xth harmonic only,

$$e_x = \left\{LD + \left(r - \frac{gM - aL}{C}\right) + \frac{1 + ar}{CD}\right\} i_x \text{ (approx.)}$$

from which on replacing D by $jx\omega$ we obtain

$$i_x = \frac{e_x}{r - (gM - aL)/C + j\{x\omega L - (1 + ar)/x\omega C\}}$$
$$= \frac{e_x}{r - (gM - aL)/C + j\omega L(x^2 - n^2)/x}$$
$$= \frac{e_x}{j\omega L(x^2 - n^2)/x} \text{ (approx.)} \quad . \quad . \quad . \quad . \quad . \quad (27)$$

since $r - (gM - aL)/C$ is negligible compared with $\omega L(x^2 - n^2)/x$

$$\therefore \frac{i_n}{i_x} = j\frac{e_n}{e_x} \cdot \frac{x^2 - n^2}{x} \cdot \frac{\omega L}{r - (gM - aL)/C}$$
$$\therefore \frac{I_n''}{I_x''} = \frac{E_n}{E_x} \cdot \frac{x^2 - n^2}{x} \cdot \frac{\omega L}{r - (gM - aL)/C} \quad . \quad (28)$$

By considering the ordinary circuit without valve amplification as a special case of the valve circuit in which the constants g and a are both taken as zero, instead of working it out direct, the necessary calculations can be somewhat reduced.

Thus for this case we have at once, from Equation (28),

$$\frac{I_n'}{I_x'} = \frac{E_n}{E_x} \cdot \frac{x^2 - n^2}{x} \cdot \frac{\omega L}{r} \quad . \quad . \quad . \quad (29)$$

where for the circuit shown in Fig. 8 with two inductance coils in the oscillatory circuit

L = total inductance in oscillatory circuit
$= L_1 + L_2$

and r = total effective resistance of oscillatory circuit.

To find r in terms of r_1 and r_2 the actual resistances of the two coils, and R, the value of the high non-inductive resistance shunting coil 1, we have

$$e_n = (L_1D + r_1)i_n + \left(L_2D + r_2 + \frac{1}{CD}\right)i_c$$
$$= \left\{(L_1 + L_2)D + r_1 + r_2 + \frac{1}{CD}\right\}i_n$$
$$- \left\{L_2D + r_2 + \frac{1}{CD}\right\}i_r \text{ (since } i_c = i_n - i_r)$$

but $i_r = -\dfrac{1}{R}(L_1D + r_1)i_n$

$$\therefore e_n = \left\{\frac{L_1L_2}{R}D^2 + \left(L_1 + L_2 + \frac{L_1r_2 + L_2r_1}{R}\right)D + \left(r_1 + r_2 + \frac{L_1}{CR} + \frac{r_1r_2}{R}\right) + \left(\frac{1}{C} + \frac{r_1}{CR}\right)\frac{1}{D}\right\}i_n$$

which has as its particular integral

$$e_n = \left[r_1 + r_2 - \frac{n^2\omega^2L_1L_2}{R} + \frac{L_1}{CR} + \frac{r_1r_2}{R} + j\left\{n\omega\left(L_1 + L_2 + \frac{L_1r_2 + L_2r_1}{R}\right) - \frac{1}{n\omega C}\left(1 + \frac{r_1}{R}\right)\right\}\right]i_n$$

from which, on using the relation $n^2\omega^2(L_1 + L_2)C = 1$, which is approximately true, and neglecting r_1r_2/R, we see that effective resistance $r = r_1 + r_2 + \dfrac{n^2\omega^2L_1^2}{R}$. (30)

To find E_n/V_n we have

$$V_n = I_n' n\omega L_1 \text{ (approx.)}$$
$$= E_n\frac{n\omega L_1}{r}$$

or

$$E_n = V_n\left(\frac{r_1 + r_2}{n\omega L_1} + \frac{n\omega L_1}{R}\right) \quad . \quad . \quad . \quad (31)$$

To find V_x/V_n for the circuit with valve we have

$$\frac{V_x}{V_n} = \frac{I_x''}{I_n''} \cdot \frac{x}{n}$$
$$= \frac{E_x}{E_n} \cdot \frac{x^2}{x^2 - n^2} \cdot \frac{r''}{n\omega L} \text{ [from (28)]} \quad . \quad . \quad (32)$$

APPENDIX 7.

To Find the Error in the Dynamometer Reading Due to the Auxiliary Current, not being Sinusoidal, the Harmonic being Calculated from the Differences of the Two Sets of Readings.

Let d' = dynamometer reading without amplification.
d'' = dynamometer reading with amplification.
V_n' = resonating voltage (max. value) without amplification.
V_n'' = resonating voltage (max. value) with amplification.
k = d.c. calibration constant of dynamometer.

Assuming that the valve is worked on the straight portion only of its characteristic and that the pressure-coil current does not change in the interval between the readings, then

$$d' = \frac{k}{2}\left(\sum_{x=1}^{x=n-2} I_x I_x' \cos\theta_x + I_n I_n' + \sum_{x=n+2}^{x=\infty} I_x I_x' \cos\theta_x\right)$$

and $$d'' = \frac{k}{2}\left\{\sum_{x=1}^{x=n-2} I_x I_x'' \cos(\theta_x + \mu_x) + I_n I_n'' + \sum_{x=n+2}^{x=\infty} I_x I_x' \cos(\theta_x + \mu_x)\right\}$$

where μ_x = change in phase of xth harmonic current in oscillatory circuit relative to xth harmonic current in the pressure coil, due to the effect of the valve.

$$\therefore d'' - d' = \frac{k}{2}\left[\sum_{n=1}^{x=n-2} I_x\{I_x'' \cos(\theta_x + \mu_x) - I_x' \cos\theta_x\} + I_n(I_n'' - I_n') + \sum_{x=x+2}^{x=\infty} I_x\{I_x'' \cos(\theta_x + \mu_x) - I_x' \cos\theta_x\}\right]$$

With no interfering harmonics in the auxiliary current we should have

$$d'' - d' = \tfrac{1}{2}kI_n(I_n'' - I_n') = \frac{kI_n}{2n\omega L_1}(V_n'' - V_n')$$

$$\therefore \frac{\text{error}}{\text{fundamental}} = \sum_{x=1}^{x=\infty} \frac{I_x}{I_1} \cdot \frac{\{I_x'' \cos(\theta_x + \mu_x) - I_x' \cos\theta_x\}}{I_n'' - I_n'} \quad (33)$$

Let $I_n''/I_n' = A$ = amplification factor.

The only effect of the valve circuit is, as shown in Appendix 7, to reduce the effective resistance of the oscillatory circuit from r to r/A, and to change the effective capacity of the circuit from C to $C/(1 + ar)$. This latter does not, however, affect the reactance component of the impedance to the xth harmonic, for this is

$$x\omega L - \frac{1 + ar}{x\omega C} = \frac{(x^2 - n^2)\omega L}{x} \text{ (since } n^2\omega^2 LC = 1 + ar)$$

$$\therefore \frac{I_x''}{I_x'} = \left[\frac{r^2 + \{\omega L(x^2 - n^2)/x\}^2}{(r/A)^2 + \{\omega L(x^2 - n^2)/x\}^2}\right]^{\frac{1}{2}}$$

$$= \left[1 + \left\{\frac{rx}{\omega L(x^2 - n^2)}\right\}^2\left(1 - \frac{1}{A^2}\right)\right]^{\frac{1}{2}} \text{ (approx.)}$$

$$= 1 + \frac{1}{2}\left(1 - \frac{1}{A^2}\right)\left(\frac{rx}{\omega L(x^2 - n^2)}\right)^2 \text{ (approx.)}$$

If $\gamma_x = \frac{1}{2}\left(1 - \frac{1}{A^2}\right)\left(\frac{rx}{\omega L(x^2 - n^2)}\right)^2$ then $I_x''/I_x' = 1 + \gamma_x$, where γ_x is small,

also μ_x = change in phase of i_x relative to induced E.M.F. e_x

= − (change in phase of impedance vector relative to je_x)

$$= -\left[-\arctan\left\{\frac{rx/A}{\omega L(x^2 - n^2)}\right\} + \arctan\left\{\frac{rx}{\omega L(x^2 - n^2)}\right\}\right]$$

$$= -\frac{\{1 - (1/A)\}rx}{\omega L(x^2 - n^2)} \text{ (approx.)}$$

On substituting for I_x'' and I_n'' in (33) we obtain

$$\frac{\text{error}}{\text{fundamental}} = \sum_{x=1}^{x=\infty} \frac{I_x}{I_1} \cdot \frac{I_x'}{I_n'(A - 1)}\{(1 + \gamma_x)(\cos\theta_x \cos\mu_x - \sin\theta_x \sin\mu_x) - \cos\theta_x\}$$

$$= \sum_{x=1}^{x=\infty} \frac{I_x I_x'}{I_1 I_n'(A - 1)}\{(1 + \gamma_n)(\cos\theta_x - \mu_x \sin\theta_x) - \cos\theta_x\} \text{ (approx.)}$$

$$= \sum_{x=1}^{x=\infty} \frac{I_x I_x'}{I_1 I_n'(A - 1)}(\gamma_x \cos\theta_x - \mu_x \sin\theta_x) \text{ (approx. to 1st order)}$$

$$< \sum_{x=1}^{x=\infty} \frac{I_x I_x'}{I_1 I_n'(A - 1)}(|\gamma_x| + |\mu_x|)$$

$$= \sum_{x=1}^{x=\infty} \frac{I_x I_x'}{I_1 I_n'(A - 1)} \cdot \frac{\{1 - (1/A)\}rx}{\omega L(x^2 - n^2)}\left(1 + \left|\frac{\{1 + (1/A)\}rx}{2\omega L(x^2 - n^2)}\right|\right)$$

$$= \sum_{x=1}^{x=\infty} \frac{I_x I_x'}{I_1 I_n'} \cdot \frac{rx}{A\omega L(x^2 - n^2)} \text{ (approx.)}$$

The ratio of the xth term of this series to the xth term in the series for the error with the single-reading method with no amplification is given by

$$\frac{rx}{A\omega L(x^2 - n^2)} \leqslant \frac{3}{8} \cdot \frac{r}{A\omega L}$$

$\therefore$ Total max. error $\leqslant \frac{3}{8} \cdot \frac{r}{A\omega L}$ times max. error in single-reading method for given r/L, r/L being always taken to mean the effective ratio without amplification.

If maximum error in determination of nth harmonic by single-reading method is ψ_n for an r/L of 15, then maximum error for present method

$$\leqslant \frac{3}{8} \cdot \frac{r}{A\omega L} \cdot \frac{r/L}{15}\psi_n \text{ since error} \propto r/L$$

$$= \frac{r^2}{40A\omega L^2}\psi_n$$

APPENDIX 8.

To Find the Increase in I'_x/I'_n Due to the Valve being worked beyond the Straight Part of its Characteristic.

If the range of variation of the anode current does not exceed about 80 per cent of the saturation current, a good approximation can be made to the grid and anode characteristics by taking

$$i_a = gv_g + hv_g^3 + av_a + bv_a^3$$

where i_a, v_g and v_a are measured from the mid-point of the characteristic from which the valve is worked.

The only appreciable undesired harmonics of order x induced in the oscillatory circuit will be those resulting from the large nth harmonic current in this circuit.

If the resonating current $= I'_n \sin n\omega t$

$$v_g = Mn\omega I'_n \cos n\omega t \quad . \quad . \quad . \quad . \quad (34)$$

also

$$v_a = -Ln\omega I'_n \cos n\omega t \quad . \quad . \quad . \quad (35)$$

$$\begin{aligned}\therefore i_a &= n\omega I'_n(gM - aL)\cos n\omega t \\ &\quad + n^3\omega^3 I'^3_n(hM^3 - bL^3)\cos^3 n\omega t \\ &= n\omega I'_n(gM - aL)\cos n\omega t \\ &\quad + \{n^3\omega^3 I'^3_n(hM^3 - bL^3)\}\tfrac{1}{4}(3\cos n\omega t + \cos 3n\omega t)\end{aligned}$$

The only harmonic in the anode current other than the nth is one of order $3n$, which is of magnitude

$$= \frac{n^3\omega^3 I'^3_n}{4}(hM^3 - bL^3)$$

The proportion of this current passing through the main inductance is in the ratio of the admittance of the inductance to that of the whole oscillatory circuit, that is

$$\frac{-j\{1/(3n\omega L)\}}{-j\{1/(3n\omega L)\} + j3n\omega C} \text{ (approx.)}$$

$$= \frac{1}{1 - 9n^2\omega^2 LC} = -\frac{1}{8}$$

$$\therefore I'_{3n} = \frac{1}{32}\{n^3\omega^3 I'^3_n(hM^3 - bL^3)\}$$

$$\leqslant \frac{1}{32}n^3\omega^3 I'^3_n hM^3$$

$$\therefore \frac{I'_{3n}}{I'_n} \leqslant \frac{1}{32}hn\omega M V_g^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (36)$$

since V_g = max. grid voltage above mean voltage $= Mn\omega I'_n$ [from (34)]

The amplification $A = \dfrac{r}{r - (gM - aL)/C}$ (from Appendix 6)

$$= \frac{r}{r - gM/C} \text{ (approx.)}$$

$$\therefore M = \frac{Cr\{1 - (1/A)\}}{g}$$

$$= \frac{r\{1 - (1/A)\}}{n^2\omega^2 Lg} \quad . \quad . \quad . \quad . \quad (37)$$

$\therefore$ substituting for M in (36) we get

$$\frac{I'_{3n}}{I'_n} \leqslant \frac{rh\{1 - (1/A)\}V_g^2}{32n\omega Lg}$$

$$< \frac{rhV_g^2}{32n\omega Lg} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (38)$$

APPENDIX 9.

To Find the Error Due to the Reading of the Voltmeter Across the Main Inductance being Influenced by the Presence of the Interfering Harmonics in the Oscillatory Current.

The voltmeter across the inductance measures

$$\frac{1}{\sqrt{2}}(V_1^2 + V_3^2 + V_5^2 + \ldots V_n^2 + \ldots)^{\frac{1}{2}}$$

$$= \frac{V_n}{\sqrt{2}}\left[\left(\frac{V_1}{V_n}\right)^2 + \left(\frac{V_3}{V_n}\right)^2 + \ldots + 1 + \left(\frac{V_{n+2}}{V_n}\right)^2 + \ldots\right]^{\frac{1}{2}}$$

The error made by taking this reading as the resonating voltage of the nth harmonic is given by

$$\frac{\text{error}}{\text{true reading}} = \left[1 + \sum_{x=1}^{x=\infty}\left(\frac{V_x}{V_n}\right)^2\right]^{\frac{1}{2}} - 1$$

$$= \frac{1}{2}\sum_{x=1}^{x=\infty}\left(\frac{V_x}{V_n}\right)^2 \text{ (approx.)}$$

$$= \frac{1}{2}\sum_{x=1}^{x=\infty}\left(\frac{E_x}{E_n}\cdot\frac{x^2}{x^2 - n^2}\cdot\frac{r''}{n\omega L}\right)^2 \text{ (on substituting for } V_x/V_n \text{ from Appendix 6)}$$

$$= \frac{1}{2}\left(\frac{r''}{n\omega L}\right)^2\sum_{x=1}^{x=\infty}\left(\frac{E_x}{E_n}\cdot\frac{x^2}{x^2 - n^2}\right)^2 \quad . \quad . \quad (39)$$

To find the error made in the estimation of the nth harmonic of a wave, due to the errors made in the two readings of the resonating voltage before and after amplification, we have

$$d'' - d' = \tfrac{1}{2}kI_n(I''_n - I'_n)$$

$$= \frac{kI_n}{2n\omega L_1}(V''_n - V'_n)$$

$$\therefore I_n = \frac{2(d'' - d')n\omega L_1}{k(V''_n - V'_n)}$$

Now

$$\delta I_n = \frac{\partial I_n}{\partial V''_n}\delta V''_n + \frac{\partial I_n}{\partial V'_n}\delta V'_n$$

where δI_n is the total error in I_n due to errors $\delta V''_n$ and $\delta V'_n$ in V''_n and V'_n respectively.

$$\therefore \delta I_n = \frac{2(d'' - d')n\omega L}{k}\left\{-\frac{\delta V''_n}{(V''_n - V'_n)^2} + \frac{\delta V'_n}{(V''_n - V'_n)^2}\right\}$$

$$= I_n\left\{\frac{\delta V'_n}{V''_n - V'_n} - \frac{\delta V''_n}{V''_n - V'_n}\right\}$$

$$\therefore \frac{\delta I_n}{I_n} = \frac{1}{A - 1}\cdot\frac{\delta V'_n}{V'_n} - \frac{A}{A - 1}\cdot\frac{\delta V''_n}{V''_n} \quad . \quad (40)$$

But the error $\propto \left(\frac{r''}{L}\right)^2$ [from (39)]

$$\propto \left(\frac{1}{A}\right)^2$$

$$\therefore \frac{\delta V_n''}{V_n''} = \frac{\delta V_n'}{V_n'} \cdot \frac{1}{A^2}$$

Substituting for $\frac{\delta V_n''}{V_n''}$ in (40) we have

$$\frac{\delta I_n}{I_n} = \left(\frac{1}{A-1} - \frac{1}{A(A-1)}\right)\frac{\delta V_n'}{V_n'}$$

$$= \frac{1}{A} \cdot \frac{\delta V_n'}{V_n'}$$

$$= \frac{1}{2A}\left(\frac{r''}{n\omega L}\right)^2 \sum_{x=1}^{x=\infty}\left(\frac{E_x}{E_n} \cdot \frac{x^2}{x^2 - n^2}\right)^2 \quad . \quad . \quad (41)$$

The above infinite series can be shown to be convergent for the values of E_x/E_n given by the neon-lamp induced E.M.F. wave, by considering separately the two ranges of x, 1 to x_0, and $x_0 + 2$ to ∞, where x_0 is an odd integer greater than the largest value of n required. All the terms of the first section are finite, while the second section is easily shown to be convergent by comparison with the appropriate infinite integral.

APPENDIX 10.

To Find the Error in the Dynamometer Reading Due to the Beat Frequency being too Near to the Natural Frequency of the Moving System.

The differential equation for the motion of the moving system is

$$(aD^2 + bD + c)\theta$$
$$= T\left\{I_n' \sin\left(n(\omega + \delta\omega)t + \phi_n'\right)\right\}\left\{I_n \sin(n\omega t + \phi_n)\right.$$
$$\left. + \sum_{x=1}^{x=\infty} I_x \sin(x\omega t + \phi_x)\right\} \quad . \quad . \quad . \quad . \quad . \quad (42)$$

assuming that the auxiliary current is sinusoidal and given by

$$I_n' \sin\left\{n(\omega + \delta\omega)t + \phi_n'\right\}$$

where θ = displacement of moving system from its equilibrium position, in radians,
a = moment of inertia of moving system,
b = torque opposing motion, exerted on moving system by damping medium per unit angular velocity,
c = control torque per unit angular displacement,
T = torque on moving system due to unit current in each of fixed and moving coils.

From (42) we have

$$(aD^2 + bD + c)\theta = \frac{TI_n'}{2}\Big[I_n\{\cos(n\delta\omega t + \phi_n' - \phi_n)$$
$$- \cos(\overline{n2\omega + \delta\omega t} + \phi_n' + \phi_n)\}$$
$$+ \sum_{x=1}^{x=\infty} I_x\{\cos[(\overline{n - x\omega} + n\delta\omega)t + \phi_n' - \phi_x]$$
$$- \cos[(\overline{n + x\omega} + n\delta\omega)t + \phi_n' + \phi_x]\}\Big]$$

Considering only that harmonic of the torque given by $\frac{1}{2}TI_nI_n' \cos(n\delta\omega t + \phi_n' - \phi_n)$, which is obviously by far the most important, then

$$(aD^2 + bD + c)\theta = \tfrac{1}{2}TI_nI_n' \cos(n\delta\omega t - \theta_n)$$

where $\theta_n = \phi_n - \phi_n'$.

The particular integral only is required for the solution of this equation, as the reading will not be taken during the initial transition period.

This solution is given by

$$\theta = \frac{1}{\sqrt{\{(c - ap^2)^2 - b^2p^2\}}}\tfrac{1}{2}TI_nI_n'$$
$$\sin\left(pt - \theta_n + \arctan\frac{bp}{c - ap^2}\right)$$

where p is written for $n\delta\omega$.

If time is measured from the instant when $\theta = 0$, we have

$$\theta = \frac{1}{\sqrt{\{(c - ap^2)^2 - b^2p^2\}}}\tfrac{1}{2}TI_nI_n' \sin pt \quad . \quad (43)$$

The above expression is most useful when given in terms of the ratios of actual to critical damping, and impressed to natural frequency.

For critical damping $b_0^2 = 4ac$, where b_0 = critical damping factor.

$\therefore$ if b/b_0 = ratio of actual damping factor to critical damping factor
$= \lambda$

then $$b^2 = 4ac\lambda^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (44)$$

Also if $p_0 = 2\pi$ (natural frequency)

$$p_0^2 = \frac{c}{a} \text{ (approx., if } b \text{ is small)}$$

If $\frac{p}{p_0}$ = ratio of impressed to natural frequency
$= \beta$

then $$p^2 = \frac{c\beta^2}{a} \quad . \quad . \quad . \quad . \quad . \quad . \quad (45)$$

Substituting in (43) from (44) and (45) we have

$$\theta = \frac{1}{\sqrt{\{(c - c\beta^2)^2 + 4c^2\beta^2\lambda^2\}}}\tfrac{1}{2}TI_nI_n' \sin pt$$
$$= \frac{1}{\sqrt{\{(1 - \beta^2)^2 + 4\beta^2\lambda^2\}}} \cdot \frac{TI_nI_n'}{2c} \sin pt \quad . \quad (46)$$

If true reading = max. reading with no damping and inertia effects then true reading $= \frac{TI_n I'_n}{2c}$

$$\therefore \frac{\text{actual reading}}{\text{true reading}} = \frac{1}{\sqrt{\{(1-\beta^2)^2 + 4\beta^2\lambda^2\}}} = \delta$$

The variation of δ with β is shown in Fig. 24 for several values of λ. It is seen that the best damping is that which makes $\lambda = 0{\cdot}707$, as then the beat frequency can be up to 40 per cent of the natural frequency of the moving system without the error exceeding 1 per cent of the maximum reading.

The other harmonics in the torque are given by

$$-\tfrac{1}{2}TI'_n I_n \cos\{n(2\omega+\delta\omega)t + \phi'_n + \phi_n\}$$
$$+\frac{TI'_n}{2}\sum_{x=1}^{x=\infty} I_x[\cos\{(\overline{n-x\omega}+n\delta\omega)t + \phi'_n - \phi_x\}$$
$$-\cos\{(\overline{n+x\omega}+n\delta\omega)t + \phi'_n + \phi_x\}]$$

Then taking $\lambda = 0{\cdot}707$ we have $\delta < 1/\beta^2$ for each harmonic of torque, and since, owing to the arbitrary distribution of phase angles in the above series, the amplitude of resultant deflection is less than the sum of the amplitudes of deflections due to separate harmonics in the torque, we have at once

extra deflection

$$< \frac{TI'_n I_n}{2c}\left\{\frac{p_0^2}{4n^2\omega^2} + \sum_{x=1}^{x=\infty}\frac{I_x p_0^2}{I_n\omega^2}\left(\frac{1}{(n-x)^2}+\frac{1}{(n+x)^2}\right)\right\} \quad . \quad (47)$$

$$\therefore \frac{\text{error}}{\text{fundamental}} < \frac{p_0^2 I_n}{4n^2\omega^2 I_1} + \frac{p_0^2}{\omega^2}\sum_{x=1}^{x=\infty}\frac{I_x}{I_1}\left\{\frac{1}{(x-n)^2} + \frac{1}{(x+n)^2}\right\}$$

The error will in general be less than that which obtains for the analysis of a rectangular wave, and so, taking $I_x/I_1 = 1/x$ and considering the infinite series in two sections as before, it can be shown that

$$\frac{\text{error}}{\text{fundamental}} < \frac{p_0^2}{\omega^2}\left\{\frac{1}{4n^3} + \frac{5}{16}(1+\tfrac{1}{2}\log_e x_0) + \frac{1}{x_0^2-n^2} + \frac{1}{n^2}\log_e\left(1-\frac{n^2}{x_0^2}\right)\right\}$$

The above error is greatest for $n = 3$, for which case, taking natural period of moving system = 1 sec., frequency of wave being analysed = 50 and $x_0 = 31$, we have maximum possible error $< 0{\cdot}034$ per cent of fundamental. The actual error is likely to be much less than this, and so will in general be quite negligible.

APPENDIX 11.

To Find the Error in the Dynamometer Reading Due to the Interfering Harmonics Induced in the Oscillatory Circuit by the Valve.

If the valve is worked at the middle of its characteristic the only appreciable harmonics induced in the oscillatory current will be odd harmonics of the fundamental wave, i.e. referring to the wave being analysed the interfering harmonics in the oscillatory circuit are denoted by I'_{3n}, I'_{5n}, I'_{7n}, etc., or by $\Sigma I'_{yn}$, where y is an odd integer differing from unity.

The torque produced by one of these harmonics in the fixed-coil current reacting with all the harmonics in the moving-coil current is

$$\tfrac{1}{2}TI'_{yn}\sum_{x=1}^{x=\infty} I_x[\cos\{(\overline{yn-x\omega}+yn\delta\omega)t + \phi'_{yn} - \phi_x\}$$
$$-\cos\{(\overline{yn+x\omega}+yn\delta\omega)t + \phi'_{yn} + \phi_x\}]$$

where the range of x includes $x = n$.

The maximum error will be expected from the terms for which $x = yn$, and so these terms will be considered separately.

For a single value of y, i.e. considering only one of the interfering harmonics in the oscillatory current and excluding the term for $x = yn$ from the summation, we obtain from Equation (47), Appendix 10,

$$\frac{\text{error}}{\text{true reading}} < \frac{p_0^2}{\omega^2}\sum_{x=1}^{x=\infty}\frac{I'_{yn}}{I'_n}\cdot\frac{I_x}{I_n}\left\{\frac{1}{(yn-x)^2}+\frac{1}{(yn+x)^2}\right\} \quad . \quad (48)$$

For a self-oscillatory circuit the effective resistance of the circuit is made negative and then the oscillations increase until the saturation current is reached, this being the limiting factor. As a consequence of this the anode current waves are flattened on top and so contain harmonics other than the fundamental.

The anode-current wave will be smooth and without ripples, and so we can expect the harmonics in it to be less than the corresponding harmonics in a rectangular wave.

If Ia_n and Ia_{yn} are the harmonics in the anode current of order n and yn respectively, referred to the wave being analysed as fundamental, and if the oscillatory circuit is tuned to the nth harmonic, then the anode current divides between the two paths of the oscillatory circuit in the ratio of their admittances

$$\frac{I'_{yn}}{Ia_{yn}} = \frac{-j\{1/(yn\omega L)\}}{-j\{1/(yn\omega L)\} + jyn\omega C} \text{ (approx.)}$$
$$= \frac{1}{1-y^2}$$

Also $$\frac{I'_n}{Ia_n} = \frac{-j\{1/(n\omega L)\}}{r/(n^2\omega^2L^2) - j1/(n\omega L) + jn\omega C} \text{ (approx., neglecting } r^2 \text{ compared with } n^2\omega^2L^2\text{)}$$
$$= -j\frac{n\omega L}{r}$$

but $$\frac{Ia_{yn}}{Ia_n} = \frac{1}{y} \text{ for a rectangular wave}$$

$$\therefore \frac{I'_{yn}}{I'_n} = \frac{r}{y(y^2-1)n\omega L} \quad . \quad . \quad . \quad (49)$$

The error will be less for most waves likely to be considered than for the case of the rectangular wave for which, on substituting in Equation (48), we have

$$\frac{\text{error}}{\text{fundamental}}$$
$$< \frac{p_0^2 r}{n\omega^3 Ly(y^2-1)}\left\{F(1) + \tfrac{1}{2}\int_1^{yn-2} F(x)dx + F(yn+2) + \tfrac{1}{2}\int_{yn+2}^{\infty} F(x)dx\right\}$$

where $F(x) = \dfrac{1}{x(yn-x)^2} + \dfrac{1}{x(yn+x)^2}$, the term for $x = yn$ being excluded from the summation.

On evaluating this expression and putting $n = 3$, since the error is greatest for this case, we have

$$\frac{\text{error}}{\text{fundamental}} < \frac{0\cdot 8rp_0^2}{3\omega^3 Ly(y^2-1)}$$

Therefore, considering all possible values of y from 3 to ∞, we obtain

$$\frac{\text{error}}{\text{fundamental}} < \frac{0\cdot 27rp_0^2}{\omega^3 L}\left\{\frac{1}{24} + \sum_{y=5}^{y=\infty}\frac{1}{y(y^2-1)}\right\}$$
$$< \frac{0\cdot 27rp_0^2}{\omega^3 L}\left\{\frac{1}{24} + \tfrac{1}{2}\int_3^{\infty}\frac{dy}{y(y^2-1)}\right\}$$
$$< \frac{0\cdot 02rp_0^2}{\omega^3 L}$$

For $r/L = 200$, $\omega = 314$, and natural period of moving system $= 1$ sec., this error is less than $0\cdot 0006$ per cent of the fundamental, and is thus quite negligible.

Considering now the terms in the series for the torque for which $x = yn$, we have

$$\text{torque} = \tfrac{1}{2}T\sum_{y=3}^{y=\infty} I'_{yn}I_{yn}\{\cos(yn\delta\omega t + \phi'_{yn} - \phi_{yn}) - \cos(yn2\omega + \delta\omega t + \phi'_{yn} + \phi_{yn})\}$$

which gives

$$\frac{\text{error}}{\text{true reading}} < \sum_{y=3}^{y=\infty}\frac{I'_{yn}}{I'_n}\cdot\frac{I_{yn}}{I_n}\left(\frac{p_0^2}{y^2n^2\delta\omega^2} + \frac{p_0^2}{4y^2n^2\omega^2}\right)$$

On substituting for I'_{yn}/I'_n from (49), and taking $I_{yn}/I_n < 1/y$, since the error will in general be less than that for the analysis of a rectangular wave, we have

$$\frac{\text{error}}{\text{true reading}} < \frac{p_0^2 r}{n^3\omega L}\left(\frac{1}{\delta\omega^2} + \frac{1}{4\omega^2}\right)\sum_{y=3}^{y=\infty}\frac{1}{y^4(y^2-1)}$$
$$< \frac{p_0^2 r}{n^3\omega L}\left(\frac{1}{\delta\omega^2} + \frac{1}{4\omega^2}\right)\left\{\frac{1}{648} + \frac{1}{2}\int_3^{\infty}\frac{dy}{y^4(y^2-1)}\right\}$$
$$= \frac{0\cdot 0023p_0^2 r}{n^3\omega L\delta\omega^2}\ \text{(approx.)}$$
$$= \frac{0\cdot 0023r}{n\omega\beta^2 L}\ (\text{since } \beta = n\delta\omega/p_0)$$

Taking $\beta = 0\cdot 4$ and $\omega = 314$, the maximum possible error is less than $0\cdot 0046r/(nL)$ per cent of true reading.

For $n = 3$, for which case it is greatest, the error is less than $0\cdot 0016r/L$ per cent of true reading.

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NOTE:—Much of this bibliography has been obtained from item (83) in the above list.

DISCUSSION BEFORE THE INSTITUTION, 6 NOVEMBER, 1924.

Dr. C. V. Drysdale: Anyone who has had actual experience of wave-form analysis will agree with the authors that the old methods of separating out the harmonics from a single wave-trace are tedious and inaccurate, and there can be no question that a direct electrical method of measuring the harmonics is greatly to be preferred. They have certainly shown by their careful theoretical analysis and experimental examples that the method proposed by them is capable of a high degree of accuracy; and the neon-lamp method of obtaining the various frequencies for the analysing wave is certainly most highly ingenious and valuable for many purposes. There are, however, certain directions in which it appears to me that the electrical method could be improved while retaining the fundamental principle employed by the authors. It will be noticed that one of the reasons for their attempts at deriving the high-frequency analysing wave directly from the machine under test is that, on account of the comparatively large periodic time of their dynamometer instrument, it is necessary to maintain the analysing and test waves in synchronism over a moderately long period, and this is difficult to do unless they originate from the same source. If the periodic time of the wattmeter could be reduced to 0·1 second or less, so as still to give the average value of the product of the two components while being able to follow beats of the order of a few periods per second, the whole procedure would be greatly simplified, and it would be possible to obtain the analysing wave from a separate oscillating set and to tune it sufficiently closely to be able to obtain the maximum deflection without the need for holding it in exact phase relation for any considerable length of time. Although for ordinary accurate measurements of power I have always championed the dynamometer wattmeter against its electrostatic and other rivals, this is a case in which the electrostatic or hot-wire form of wattmeter in which the moving element can be made very light and will consequently have a very small periodic time can be used with advantage, with the additional benefit that all difficulties concerning self-inductance or mutual inductance in the wattmeter disappear and that the observing instruments become commercially procurable. The simple form of string electrometer made by the Cambridge and Paul Instrument Co. and other firms is extremely suitable for this purpose, as the moving element is only a thin fibre having a periodic time of only a few hundredths of a second, which time can be varied over a considerable range by adjusting the tension. One of my assistants, Mr. G. F. Partridge, B.Sc., has developed a system of harmonic analysis originated by Mr. B. S. Smith, in which a valve-generated analysing wave is used to polarize the plates of a string electrometer while the string is connected to the source to be analysed.

The frequency of the analysing wave can be varied continuously by the rotation of a variometer, the motion of the string being photographed on a drum rotating with the variometer. Frequencies of 50 periods per sec. and upwards can be produced with ease, and by changing the capacity in the oscillating circuit the frequency can be varied over a very wide range with an approximately constant E.M.F. Fig. A shows the connections of the electrometer, from which it will be seen that the E.M.F. to be analysed is merely applied between the string and the mid-point between the attracting plates or "quadrants," and the analysing E.M.F. is applied across the quadrants themselves, as in the standard connections for electrostatic wattmeters. In the ordinary form of Cambridge string electrometer employed the camera is coupled to the variable oscillator for producing the analysing wave. The variometer is coupled to the rotating drum of the camera and to a motor which enables the two to be run in perfect correspondence at any desired speed. There is therefore a definite oscillating frequency corre-

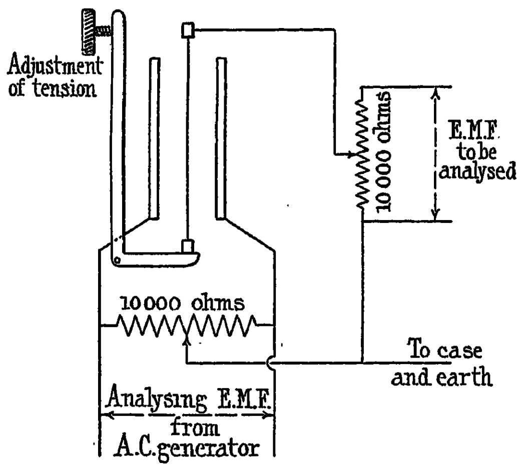


Fig. A.—Method of connecting string electrometer.

sponding to each angular position of the rotating drum, which can be determined initially; and it is possible to arrange the oscillator circuits so that an approximately constant P.D. is maintained between the quadrants or attracting plates throughout the range of frequency, in which case the maximum peaks on the record can be made to give the values of the harmonics directly. Tests made with different speeds of rotation of the variometer have given the same maxima, showing that the electrometer follows the beats accurately even when they are of moderately high frequency. This method has been used very successfully for the harmonic analysis of irregular waves of short duration, and is especially useful in the case of irregular disturbances containing a number of unrelated vibration frequencies. For the majority of practical tests on electrical machines, however, there should be no difficulty in maintaining the frequency sufficiently constant for a short time to be able to read the maximum directly, and this has been found to be easily possible. In this case the whole of the apparatus required is the string electrometer and an ordinary oscillating set with coils of sufficiently high inductance and low resistance to produce oscillations of the comparatively low frequencies required, thus reducing the whole of the gear to apparatus which is already easily obtainable. Care must, of course, be taken to work the valves over a sufficiently low range to avoid the generation of harmonics in the analysing wave, but this is not usually a difficult matter. The authors' method of producing the series of analysing waves from the machine under test by the commutator or neon-lamp method certainly has the advantage of enabling the phase as well as the magnitude of each of the harmonics to be determined, but I have never known a case in which the phase of the harmonics appears to be of great importance, and the authors do not appear to have troubled to obtain it in the tests they have recorded. It therefore appears to me that the electrometer method with a separate oscillating set

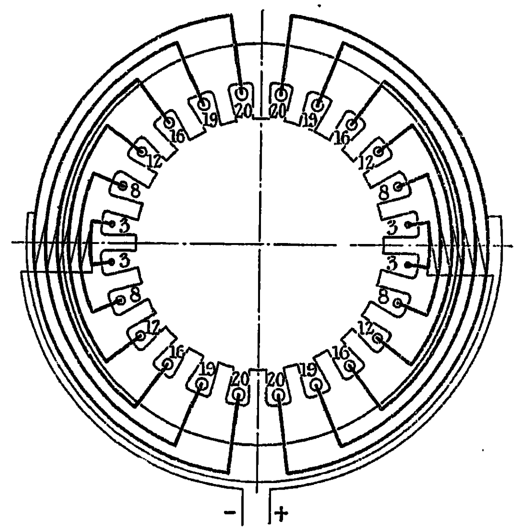


Fig. B.—Winding diagram of sine-wave alternator, showing distribution of turns in slots.

will fulfil all practical requirements; and quite possibly hot-wire elements of the Irwin type would prove almost equally suitable; and either of them could, it appears to me, be adapted to the authors' devices without difficulty.

In this connection there seems to be a great need for an alternator which will give a true sine wave for testing purposes. It occurred to me some years ago that an alternator made up with sinusoidally distributed windings on the lines of my phase-shifting transformers would give a much more perfect wave-form than is usually obtainable. Within the last few weeks a small machine has been made up on these lines. It consists simply of a stator and rotor, like an ordinary induction motor, but with distributed windings on both the stator and rotor, the distribution of turns in the slots being according to a sine law so that the flux is almost perfectly uniform across the whole diameter. The slots are staggered in order to make the effect of the teeth as small as possible, and a soft-iron shroud is inserted in the stator core to reduce this effect still further. Fig. B is a winding diagram and Fig. C an

oscillograph trace of the E.M.F. wave of a small 20-watt machine of this type which can be easily held in the hand, and it will be seen that it is almost per-

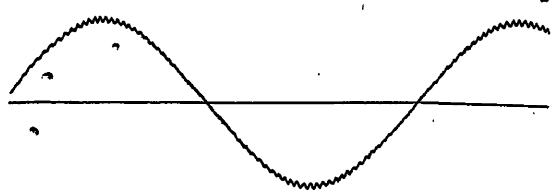


FIG. C.—Oscillograph trace of E.M.F. wave of sine-wave alternator (50 volts, 46 periods per second).

fectly sinusoidal but with a small high-frequency harmonic which corresponds approximately to the sum of the stator and rotor slots ($36 + 24 = 60$). It is probable that with a little further attention to the staggering and shrouding of the rotor these ripples could be practically eliminated; and from experiments made on the phase-shifting transformers it would appear possible to obtain a very perfect sine-wave alternator by this device. The machine shown is only a two-pole one, and consequently is only suitable for frequencies up to about 50 periods per second. A considerably higher frequency could, of course, be obtained by means of a multipolar winding, although it would probably be difficult to utilize such a winding for the frequencies required for the highest harmonics. It is thought, however, that such a machine should be of value as a testing machine for ordinary calibration, etc.

[The author's reply to the discussion will be found on page 117.]

Mersey and North Wales (Liverpool) Centre, at Liverpool, 17 November, 1924.

Prof. E. W. Marchant: Those who have had to do with the analysis of irregular wave-shapes will agree that the apparatus devised by the authors should be of practical value. Over 25 years ago I was working in Prof. Henrici's department at the City and Guilds College, using the beautiful analyser which he had devised for obtaining the amplitude of the different harmonics in a wave-shape drawn out to scale, by readings similar to those which are taken on a planimeter. The method that has to be adopted to find the harmonics to-day, even with the shortened methods of analysis that are now well known, is rather cumbrous, and, of course, when the higher harmonics of the wave have to be found it is open to error, not merely because the oscillograph itself does not record exactly the higher harmonics in the wave, as the authors have pointed out, but also because of the mechanical difficulties in analysing the curves. A slight error in going over a photographic record of the wave-shape may make an appreciable difference in the determination of the value of one of the higher harmonics. It may be well to point out, however, that even with a 20th harmonic on a 50-cycle wave, the high-frequency oscillograph will not be very far out in its record, since the frequency of the harmonic is 1 000 per second, as compared with a natural frequency of 10 000 per second for the vibrator of the oscillograph. If the apparatus described in the paper can be relied upon it will get over these difficulties, because it determines directly the value of the harmonics from the wave itself and, therefore, avoids both the errors inevitable in the recording of waves and also the mechanical errors likely to arise in the estimation of the higher harmonic from the curve, when it has been found. The circuit shown in Fig. 1 is a very useful one and its selectivity is remarkable. It is, of course, exactly the same circuit as is used in so many wireless sets in what is known as the tuned anode arrangement, and those who have had experience with this circuit will realize how selective it may be made. The values of λnx calculated in Table 1 are, I presume, values which have been found without taking account of the fact that the power factor of the condenser is not zero. If one makes correction for the power factor of the condenser, the value of r in Equation (4) will be altered by a considerable amount. If R_1rC/L is nearly unity the effect of this correction is not large, but in some calculations which I have made the value of the coefficient R_1rC/L works out at something a good deal greater than unity, and in such cases the value of r becomes important. For example, in the case of a condenser of 40 μF capacity, working on the 11th harmonic of a 50-cycle wave, assuming a power factor of 0·4 per cent, which is almost as good as can be expected, the effective resistance, i.e. the resistance which must be shunted across the condenser in order to make the circuit equivalent to one containing a condenser with this power factor, would be only 1 800 ohms, and the values of λnx in Table 1 would therefore require considerable correction. With regard to the standard method of analysis described in Section 5, it would seem likely that a good deal of trouble would be experienced in getting the square or trapezoidal wave that should be obtained by means of a commutator. The authors refer to the difficulties met with in connection with the brush gear of their "standard" arrangement when it is using the small currents that are employed with the circuit shown in Fig. 1. Even with these small currents, to judge from the experience that one has had with rubbing contacts of this kind, I think that the possibilities of irregularity are very considerable. There is a great liability to chatter if the commutator surfaces are not absolutely true and, of course, if the motor hunts at all there will be a further difficulty due to phase displacement of the wave. With regard to Fig. 15, I should like to ask what degree of accuracy has been observed in the time of the shutting off and lighting up again of the neon lamps due to the pulses of current which produce the oscillations in the dynamometer circuit. In our experience with these lamps we have found that after a lamp has been burning at a given voltage for some time it will probably take to start it a different pressure from that which was required when the lamp first began to burn, and I should think that there might be a considerable amount of irregularity

in the interval between the switching off of the pulse due to one alternation and the starting of the pulse corresponding to the next. There may also be differences between the two lamps that are arranged back to back. I should have anticipated considerable errors in the readings of the dynamometer, due to this cause. The errors that are likely to occur in this apparatus in determining the amplitude of the various harmonics of a wave have been worked out with great precision, but I am inclined to think that the accuracy that could be obtained in practice is limited. The cases in which an analyser of this kind is likely to be most useful are those in which fairly heavy machinery is employed, where the amount of power available is considerable, and in the case of a turbo-generator or a low-speed water-wheel-driven alternator I think that the slight variations which are inevitable, due to vibration and other causes, would produce a difference of more than 0·1 per cent between the successive waves given by the alternator. It is, of course, of the highest value if this instrument can be relied on to determine within 0·1 per cent or even 1 per cent the values of the harmonics to be found, but I do not think that an analysis of this accuracy will be either possible or necessary in practice. Towards the end of the paper the authors refer to the use to which the apparatus may be put, and state that the method can possibly be applied to the analysis of all forms of periodic voltage and current curves. I should like to know what is the smallest amount of power that is necessary to operate an analyser of this description. If one is attempting to analyse the waves of current that are obtained, for example, from speech in a telephone transmitter or the periodic currents that are flowing along a telephone line due to speech, it is obvious that the amount of power available for the operation of the instrument is limited. For such purposes as the determination of harmonics, which are likely to cause interference with telephone lines, the apparatus should be of the very greatest value, and for this purpose the accuracy necessary need not be very great. All that is needed is an instrument which will find what harmonics are present, and their order of magnitude. For such purposes the instrument described in the paper should be of the highest value.

Dr. F. J. Teago: The value of the proposed new method for analysing complex wave-forms is very great, provided its accuracy is demonstrated. It is not of academic interest only, since improvements in the design and manufacture of electrical apparatus can only be made when the nature and magnitude of the existing trouble are known. The difficulty is that there is no standard to which the various methods of analysing complex waves may be referred, and the sole guide in this case is the mathematical reasoning. Taking Equation (3), viz.

$$d_1 = \tfrac{1}{2}k(I_1 I_1' \cos\theta_1 + \ldots + I_n I_n' + \ldots)$$

this deflection has been measured on a dynamometer with the object of determining I_n, and d_1 will be larger than its true value by an amount depending upon the value of the sum of all the terms except the nth. The equation for the analysing current has been given as a complex wave, apparently generated by some form of oscillating circuit, although no mention is made of this in the first part of the paper. One would also suppose that the circuit is such that every term except that containing the nth harmonic is relatively small, otherwise the error in d_1 will be exceedingly large. If, however, the analysing current had been generated by some rotating machine, then it would have contained no harmonic of an order less than the nth, and the magnitude of each harmonic other than the nth would be relatively small, and the equation for d_1 would have been

$$d_1 = \tfrac{1}{2}k(I_n I_n' + I_{n+2} I_{n+2}' \cos\theta_{n+2} + \ldots)$$

and d_1 in this case cannot differ greatly from $\tfrac{1}{2}kI_nI_n'$ (since the products of small terms are negligible) and would be larger than it. In this connection also the ammeter-measured analysing current has probably been multiplied by $\sqrt{2}$. Let this value of the analysing current $= [I_n']$. The maximum value of the nth harmonic must be got from

$$[I_n] = 2d_1/k[I_n']$$

and the question is, what is the relationship between $[I_n]$ the measured maximum value, and I_n the true maximum value of the nth harmonic in the wave under analysis?

If $[I_n']$ has been obtained as suggested above, then, since

$$[I_n'] = \sqrt{(I_1'^2 + I_3'^2 + \ldots + I_n'^2 + \ldots)}$$

we have $$[I_n'] > I_n'$$

and very much greater unless I_n' is the predominant term, so that $[I_n]$ may differ greatly from I_n. If the rotating machine analysing current is considered in relation to the value of $[I_n']$ then

$$[I_n'] = \sqrt{(I_n'^2 + I_{n+2}'^2 + \ldots)}$$

and cannot differ greatly from I_n' but is rather larger than it, so that $[I_n] = 2d_1/k[I_n'] = I_n$, since the errors tend to cancel one another. On the information given in the first part of the paper the problem appears almost hopeless, but this is due to the fact that the Appendix is at the end instead of being in front.

Mr. R. O. Street: In approximating from Equation (4*a*) to Equation (4*b*) it is assumed that R_1rC/L is large compared with unity, and this does not seem consistent with the statement in the next paragraph that it is advisable to make it of the order unity.* Also, in the simplification of Equation (7) the term $r_1/(n\omega L)$ is neglected. The condition of tuning makes $n^2\omega^2LC = 1$, so that we have really neglected $n\omega r_1C$. Thus the higher the harmonic the greater is the error, and not the smaller, as would appear at first sight. Further, in obtaining Equation (10) it is assumed that $R_1\omega C/\{1 + R_1rC/L\}$ is large, and so, in virtue of the previous supposition, $R_1\omega C$ must be very large, say of the order 10 000 for anything approaching a 1 per cent accuracy. Also, $\omega L/r$ must be large, but its actual value is never greater than about 20, and is often much less. I think that in

* This has since been corrected by the authors.

neasuring the degree of accuracy of any harmonic the ırror should be referred to the harmonic itself and not o the fundamental.

Mr. F. Mercer: The third harmonic and perhaps ›thers of a correspondingly low frequency result in a oss of efficiency and therefore command attention from upply engineers, but the higher harmonics of frequencies ›etween 500 and 2 000, i.e. those in the audible range, ıre of concern to telephone engineers and it is becoming ncreasingly desirable that attempts should be made to ›liminate them either in the better design of alternators ›r by the use of filters. Hitherto no satisfactory method ıas been available for measuring the higher harmonics, ınd the authors are to be congratulated in having so ıearly approached a solution. There is one criticism I ›hould like to make in connection with the method of neasurement of current in the oscillatory circuit (Fig. 2). An electrostatic voltmeter is used which measures the voltage in conjunction with a potential divider of total resistance 200 000 ohms. It seems likely that the capacity between the plates of this instrument, even if of the order of 20×10^{-6} μF, may lead to a serious error in calculating the values of harmonics having frequencies of 500 and upwards. I should like to ask the authors whether this point was appreciated and whether a suitable correction was made for it.

Mr. R. B. Burrowes: Referring to the dynamometer, let the analysing current be given by

$$i_2 = I_{n+\epsilon} \sin \{(n + \epsilon)\omega t - \phi'_{n+\epsilon}\}, \text{ where } \epsilon < 1.$$

The product of this and the current under analysis given by

$$i_1 = I_0 + I_1 \sin (\omega t - \phi_1) + \ldots + I_n \sin (n\omega t - \phi_n) + \ldots$$

gives rise to a number of terms the integrals of which do not cancel out over the period of the fundamental, from which it might be supposed at first that the high-frequency impulses which they represent do not cancel out in their effect on the torque. But, as the authors point out, to obtain the effect on the torque we must integrate the impulses, not over the period of the fundamental, but over the period of swing of the moving system, whatever this may be. For example, putting $\epsilon = 0$, the period of the torque is infinite, that is, the torque is steady and therefore also the deflection, the torque being given by $\frac{1}{2}KI'_nI_n \cos (\phi - \phi'_n)$, so that all the harmonically varying impulses cancel out absolutely. By increasing ϵ from 0 up to $0 \cdot 5$ in steps, we can find the effect on the torque of this difference in frequency between the analysing current and the harmonic under analysis. Putting $\epsilon = 0 \cdot 1$, the low-frequency torque due to the harmonic under analysis is given by $\frac{1}{2}KI'_{n+\epsilon} I'_n \cos (0 \cdot 1\omega t + \phi'_n - \phi'_{n+\epsilon})$. That is, if the fundamental has a period of 1/50th second, this torque has a period of $\frac{1}{5}$ second. Superposed on this is a torque of high frequency $(2n + 0 \cdot 1)$ of the fundamental, which therefore almost cancels out over the longer period. The other harmonics which will produce the greatest effort will be those of frequency nearest to that under analysis. So, taking the next higher [the $(n + 1)$th], the low-frequency torque due to this and the analysing current is given by

$$\tfrac{1}{2}KI'_{n+\epsilon}I_{n+1} \cos (0 \cdot 9\omega t + \phi_{n+1} - \phi'_{n+\epsilon}),$$

i.e. it has a period of 1/45th second. Putting $\epsilon = 0 \cdot 5$, the analysing current now produces torques of equal low frequency with both the nth and the $(n + 1)$th harmonics of the current under analysis. The equal periods are double that of the fundamental, i.e. 1/25th sec. The effect of these, whether they add up or to what extent they cancel, will depend on their phase relations as well as on their amplitudes; so that in this case there will be total confusion between two consecutive harmonics, though with only odd harmonics this confusion would be less. These results seem to show that in order to get a torque effect due to only one harmonic ϵ must be less than $0 \cdot 1$, or, as the authors have it, σ must be small compared with ω. Another necessity for having ϵ less than $0 \cdot 1$ is, of course, in order to be able to observe the amplitude of the deflection. For with a fundamental frequency of 50 and $\epsilon = 0 \cdot 1$, the frequency of swing would be 5, i.e. too high to allow the deflections to be read comfortably. With a swing frequency of 1 sec., ϵ must equal 1/50. From this it appears that a very fine gradation of frequency of the analysing current is required in order to produce the torque effect due to one harmonic only. With regard to the error due to these low-frequency swings or beats being nearly equal to that of the moving system, this seems to be fully worked out in Appendix 10. I should like to ask whether the authors are able to obtain deflections of very long-period or even steady deflection, in which case the errors due to damping and resonance vanish.

Messrs. J. D. Cockcroft, R. T. Coe, J. A. Tyacke and Miles Walker (*in reply*): The very interesting instrument described by Dr. Drysdale employs the self-oscillating method described in section (8) of our paper and, in addition, makes use of an electrostatic wattmeter having a very small periodic time of swing. This type of instrument seems admirably suited to give quick readings of the watts, and thus to work well when the frequency is changing slightly, or to be used with a variometer as described by Dr. Drysdale. The periodic time of the swing must not, however, be made too small. The filar must be able to average the power throughout the cycle and not move so quickly as to give instantaneous readings of the watts. The method of producing a sinusoidal field by properly distributing the winding is very effective, as is shown by the successful operation of the phase-shifter. Small tooth-ripples are, however, very difficult to overcome. Even the skewing of the slots does not completely eliminate such ripples, on account of discontinuity of the skewed slot at each end of the stator.

The point raised by Prof. Marchant as to the effect of the power factor of the condenser on the value of r is quite a good one if paper condensers having foil of poor conductivity are employed. We know this to our cost. For a long time the ratio r/L was increased unduly by the poor condensers that were employed. By using mica condensers having good conductivity in the opposing metal surfaces the power factor is so low

as hardly to effect the value of r. For the 11th harmonic of a 50-cycle wave we should employ a condenser of only about $3\mu F$. The exact wave-form of the current obtained from the commutator does not matter much; it affects the wave-form of the analysing current to only a very small degree. The more the corners are taken off the square wave, the smaller is the interference with I'. The variation of the effect does not matter, because we measure the value of I' at the same time as we take the dynamometer reading.

With regard to the variation in the characteristics of the neon lamps, we have not noticed any difference in the two lamps that we used back-to-back. So far as the oscillograph record goes they appear to be identical. It is true that if the lamps had different characteristics there would be a slight difference in the time phase at the beginning of each half-cycle, which would make it impossible to get what should be the maximum reading of the wattmeter. It must be remembered, however, that the reading of the wattmeter would only be multiplied by the cosine of half the angle of variation induced by the lamps, and, as this angle is apparently extremely small (if it exists at all), the value of this cosine would be practically unity.

Prof. Marchant asks what is the smallest amount of power necessary to operate an analyser of this description. By making use of valves the amount of power required can be made excessively small. One of the methods that we have recently devised for providing the analysing current is shown diagrammatically in Fig. D. Instead of using the neon-lamp circuit shown in Fig. 13 the exciting coil M' is fed from the plate of a triode whose grid is excited by a voltage of a frequency corresponding to the frequency of the harmonic to be measured. The positive end of a battery B (about 60 volts) is connected by a contact maker F to the grid of the triode. A resistance R_3 of about 100 000 ohms acts as a grid leak and has one end connected to a roving contact on the battery so that the grid potential can be adjusted. When the contact is made, the grid becomes positive and a current flows in the plate circuit. When the contact is broken, the grid becomes negative and the plate current stops. The contact maker F consists of a minute brush running upon a copper plate which has been engraved and enamelled with a hard-wearing enamel so as to represent in concentric rings a number of concentric commutators having a number of bars as follows:—6, 10, 14, 18, 22, 26, 30, 34, 38, 42, etc. The disc is attached to a 2-pole synchronous motor so that on a 50-cycle circuit it runs at 3 000 r.p.m. In the 6-bar commutator three of the bars are of bright copper and the other three are of non-conducting enamel, so that at one revolution of the commutator the grid receives excitation having a frequency equal to that of the 3rd harmonic. The other concentric rings give excitation for the 5th, 7th, 9th, etc., harmonics as required. In order to take off the square corners of the wave-form of the voltage supplied to the grid, the coil L_4 is connected in series with the grid, and a condenser C_4 of very small capacity is connected across the resistance R_3. It will be seen that with this apparatus the only energy required to be taken from the circuit is that required to drive the synchronous motor, and need not be more than $\frac{1}{2}$ ampere at 100 volts (or 50 watts). If this power is not available from the circuit the voltage of which is required to be analysed, it would be possible to supply it by a combination of triode valves and relay, the grid of the first valve being connected to the circuit in question. With the analysing current provided by the excitation illustrated in Fig. D the wattmeter shown at the meeting will give a full-scale deflection when a current of 10mA flows through the moving coil. It would, of course, be possible to supply this current from the plate of a valve whose grid was connected to the supply, so that the total power would be only that required to energize the grids of two valves.

A complete reply to the points raised by Dr. Teago will be found in the Appendixes to the paper.

Mr. Street is quite right in his objection to the statement (in the advance copies of the paper) that $R_1 rC/L$ is of the order of unity. This has been corrected on page 74 and now reads "is of the order of three." In the values of λ_{nx} worked out in Table 1 this quantity $(R_1 rC/L)$ was made equal to 3. In neglecting $r_1/n\omega L$ in simplifying Equation (7), Appendix 1, it must be

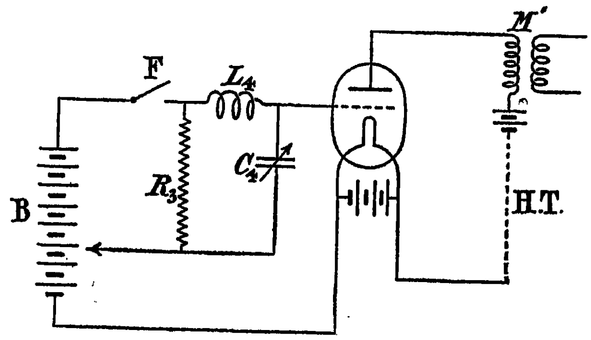


FIG. D.

remembered that r_1/L is a fixed ratio, so that the error varies as $1/n$. Mr. Street does not take into account the fact that r_1 and C are decreased with increasing n. In approximating from (9) to (10), if Rr_1C/L is made equal to three, the imaginary part of (9) is never less than 40 times the real part, so that in adding vectorially to get the ratio of the amplitudes, the real part is quite negligible.

Mr. Mercer is quite right in pointing out that where the capacity of the electrostatic voltmeter affects the voltage applied to it when obtained from a potential divider, it is necessary to make a suitable correction. The correction required in the case of the instrument employed by us is less than 1/10th of 1 per cent. In calculating this it must be remembered that the current taken by the electrostatic voltmeter is at right angles in phase to the current flowing in the potentiometer resistance, and therefore a current of a few micro-amperes when added at right angles to a few milli-amperes makes practically no difference in the virtual value of the voltage on the instrument.

Mr. Burrowes's remarks about the torques of different frequencies apply only to the method using the valve

generator. It should be remembered, however, that, as shown in Appendix 10, the response of a low-frequency moving system such as the dynamometer coil to a torque of relatively high frequency varies inversely as the square of the torque frequency, so that these higher harmonics of torque produce no appreciable effect. The magnitude of the error introduced is worked out in Appendix 10.

SOUTH MIDLAND CENTRE: CHAIRMAN'S ADDRESS

By W. Lawson, Member.

(Extract * *from Address delivered at* Birmingham, *22nd October,* 1924.)

The normal routine and details of daily toil are rarely of general interest, but in almost all our occupations we touch the fringe of a variety of matters and problems which, though outside the prescribed limits of our work, specially entice our interest or insistently induce reflection in those directions compatible with personal bent and predilections.

Such ideas as I shall endeavour to put before you are therefore of the order of by-products of those activities in which I have been concerned as a supply meter engineer, as management secretary of a Whitley works committee in a large supply undertaking and as a member of the Institution.

It has been said that the right way to study history is to start with the parish and radiate back to Egypt and Mesopotamia, and though history is not my theme the plan of this address is analogous in so far as my remarks will concern, first our Centre, then the Institution, and afterwards the electrical industry.

If one is satisfied by merely statistical evidence, it is easy to claim that this Centre is in a flourishing condition. It is, for instance, gratifying to know that our present membership (including the East Midland Sub-Centre) numbers 936 as against 421 in the year 1913. Such figures spell progress but they do not reveal the more obscure and more vital factors representing the amount of interest taken by each individual member in the affairs of the Centre and its future development, and what his conception is of the part to be played by it in furthering the prestige and influence of the whole Institution.

It would appear that we are approaching the flood-tide of electrical development in this country, and the interchange of information and ideas which is our main purpose is becoming of increasing necessity. It is extremely desirable that more papers should be forthcoming from amongst our own members so that all available special knowledge and talent should be disclosed. In this respect much good would result from the establishment of co-operation between the various Centres and Sub-Centres and by bringing them into closer touch. I suggest that it would be feasible for Local Centres to obtain from their own members, papers for informal reading at their own and adjacent Centres and Sub-Centres, and adopt a system of interchange of such papers. The papers, together with discussions thereon, could be submitted to the Papers Committee, who would decide whether or not they should be published in the *Journal*. This would create a certain amount of competition for the honour of publication, and help to assist in the framing of more varied programmes.

It is all a question of whether we are content as a body to function mechanically on set lines or wish to intensify our interests and extract the last ounce from every privilege of membership.

The welfare of the Students' Sections is a matter of prime consideration, and senior members should associate themselves as far as they are able in the various functions held by the Students, and in addition to render, when possible, individual advice and counsel. In no better way can we ensure that in the future the Institution will contain an ever increasing number of men eager to serve it.

There is one matter to which I should like to refer on which statistics are not flattering to this Centre; and it concerns not only ourselves but the whole Institution. It is one which calls for the sympathy and support of every member: I mean the Benevolent Fund. You have all received an appeal from our Hon. Treasurer of the Fund, Mr. W. J. Anderson, who is anxious to appear in that capacity as something more than a mere figure-head. It is obvious, however, that he cannot effect much without your co-operation and I implore that you will do this, not solely by subscribing but in persuading others to do likewise. Last March the then President issued a circular to all members of the Institution in which he stated that from total of 11 500 members a sum of £636 10s. in donations and subscriptions was received. This works out at an average for the year of 1s. 1¼d. per member. Viewed in this way I think you will agree that it is an insignificant sum.

The Institution is of the order of Societies that function centrifugally, and we can claim that it does a large amount of work unostentatiously and in co-operation with other bodies for objects to which it lends its support. Let us not fail in kindliness to those of our

* The technical part of the address (not included in this extract) described the handling of three special problems in metering.

own members who have fallen on evil times. We have been criticized as a body for our inability to advance the material interests of our members, and in spite of all modern tendencies we have, through sheer weight of tradition, resisted the temptation to become protective in character. If we are frank we must admit that under existing conditions this can be a handicap in individual cases but, in promoting the advancement of electrical engineering science, the Institution does indirectly foster the interests of the electrical engineer. But that does not denote any question of the reality of its ethic of "service" implied in its constitution.

It would be absurd to suppose that its members are not influenced by prevailing currents of feeling and ideas, and that it is sterilized of all forms of self-interest, so it does well to remember and preserve its best traditions. Very rightly then does it cherish the memories and aim to do justice to the fame of men of exalted character and outstanding genius, such as Faraday, the founder of the science, and Kelvin, and foster genius from the romantic age of early discovery to the maturer period of practical application.

Kelvin, the centenary of whose birth was recently celebrated, was a man of extraordinary versatility who worked in the whole field of physical science, but is it too much to claim that his greatest contribution to the service of mankind was through his work as an electrical engineer? In this connection one feels that it would have been fitting had the Kelvin Centenary been marked by a public celebration in every Centre, organized in the name of the Institution. I mention this, not by way of retrospective criticism, because it is well known that in the crush of other work and events with which the Institution was deeply engaged it was impossible to arrange for a more extensive celebration: the point I wish to bring out was that the lives of these men symbolize the underlying spirit of the Institution, and we should be mindful of this.

I think it is a matter of general agreement that the Institution should be better known amongst all thinking sections of the public, who, if they are aware of its existence, merely regard it as a body responsible for keeping a register of qualified electrical engineers. We ourselves are apt to forget the great work accomplished by the Institution in the past. It is no exaggeration to say that it was the sheet anchor of electrical engineering and the chief source of inspiration to those engaged therein for a long period when lighting and power development was struggling against archaic legislation.

It would appear that the time is ripe for someone to write the history of the Institution of Electrical Engineers. There is a wealth of material waiting for such a volume, and what a gallery of portraits of pioneers in the most fascinating period of discovery and invention in history would be contained within its pages!

Intrinsically the Institution is richly endowed with possibilities of impressing its character on the minds of those who will take a leading part in the period of reconstruction which ultimately must follow this difficult and distracting time of industrial rehabilitation.

Within its confines are men in divers positions, leading and subordinate, engaged in administrative, managerial, and business, as well as technical affairs, all more or less in direct contact with industrial problems. It is to such as these, trained to methodical investigation, and, moreover, capable of practical judgment, that we should look for some contribution to their solution. Evolved through a century of discord and misunderstanding of fundamental causes, the problems cannot be treated successfully by mere palliatives. The political atmosphere with which they have been surrounded must be removed and they must be dealt with on social and economic lines by those actually engaged in the industries. It is a matter of practical rather than theoretical consideration.

As an educational body, I believe it is within the scope of the Institution to take its part in this connection. Amongst the list of subjects that can be taken for the Associate Membership Examination is "Works management," and I suggest that to this might be added "Economics and industrial organization." A student destined to fill an important position in either the supply or manufacturing side of the industry would be infinitely better equipped for his future work and advancement if he possessed a knowledge of the design and objects of such machinery as exists for the adjustment of the differences and relationships between employers and employees. He should know something of the history and development of trade associations from the Hanseatic League to the B.E.A.M.A., and also of the origin and history of trade unions. He would, when the time came to take a hand in these matters, be properly fitted for it. Such knowledge, so far from creating in him the perilous fervour of the industrial propagandist, would induce a wholesome interest in industrial affairs.

I think it was Mr. Wordingham who said that the Institution ramifies and is bound up with the electrical industry. It cannot, therefore, hold aloof from those problems of human organization which are the concern of and affect a large proportion of its members. To these let it, if it can, be a source of instruction and guidance as undoubtedly it can be a source of inspiration.

The sixth year following the close of the European war has been of unique interest to every sort of worker in the electrical industry. The coming into power of the first Labour Government, the British Empire Exhibition, the World Power Conference, the wages dispute in the electrical industry—all these constitute a recital almost dramatic in form, and the relative prosperity of the electrical industry can at least give us one pleasurable thrill of self-satisfaction. The general outlook, however, is far from encouraging; trade depression persists and unemployment remains an unsolved problem. It is now almost universally accepted that these are the war's inevitable after-effects and must be endured. But in spite of this the deplorable fact remains that our industries have not settled down to a united effort to get to grips with their difficulties. Industrial peace still remains a dream apparently beyond realization, and no industry, prosperous or dying, can claim entire freedom from the possibility of interruption by strike or lock-out. The materialism which possesses the national soul, and the extraordinary spread of the spirit of combination permeating all classes of the community, are the

principal factors in a fierce movement towards fostering sectional rather than public interests. In the conflicts between trade unions and employers' associations the evil effects of the movement gain their chief publicity. But an equally serious, if a less conspicuous, resultant, is the multiplicity of trade organizations that are too prone to extract from the community such rewards for their services as accord with their own valuation. In the Articles of Association of even the most predatory of societies, doubtless there will be found aims and objects of altruistic design. It is the suppression of the better part of their purpose that constitutes the leading modern error of many such societies. Self-interest cannot be eliminated from human nature or from human institutions, but it can be directed to useful and beneficent ends. Indiscriminately exercised, it induces violent reactions and opposition and leads to recurring dislocations, in the adjustment of which the factor of satisfaction is a negligible quantity. One cannot help thinking that herein lies one of the greatest and most urgent problems of our day.

Another matter of grave concern is that eternal kink in the relationships between employers and employees which is still as pronounced as ever. It is the business and public duty of both to straighten this out. It originated with the introduction of the factory system and the inevitable estrangement between the two partners in production. The working class never forgave it and it became a rooted memory which, in process of time, has developed into a collective attitude. It is a psychological phenomenon which, like political antipathies, tends to persist long after the fundamental causes have been removed. Those who wait for the demise of the capitalist system, as well as those who look to the time when the forces of labour will have been spent, are merely shirking the problem. The solution must be sought at the point of origin, namely, the factory or its equivalent. Many devices have been tried, from cold scientific management to sheer benevolence. Doubtless, Arcadian conditions of employment could be instituted by rate aid or subsidy on the benevolent plan, but this would not be the act of a model employer, neither would it create the model employee. Of the recommendations in the Whitley Report, probably the most valuable was that for the formation of works committees fully representative of management and employees, for here was suggested a simple and practical means of getting down to the bed-rock of the problem. Their aim—and this is what really matters—is to establish goodwill between employer and employee. Perhaps I can express this better by saying that free discussion and frank expression of the mind of both will help to remove those obstacles which create misunderstanding and intercept the natural flow of goodwill.

Works committees can and do materially promote the comfort of the worker, and the benefits derived from them are cumulative and permanent. They should form an integral part of works organization and should be backed by all the administrative machinery to carry out their recommendations efficiently and promptly. The electrical industry has grown to a stature to be counted amongst the great industries of the world, and it is certainly the most modern. It is therefore demanded of it that it should aim at being the best organized industrially. The recent threat of a general stoppage in the electric supply industry was a reminder that we have not yet reached security in this respect. It is a matter of deep concern to every one of us, and the fact that it appears to be beyond our control does not relieve us of the responsibility of giving thought to it. The fetish of collective action, and its narrow limitations to the securing of rewards for services, has resulted in a partial suppression of the sense of personal duty and responsibility, neglect of individual values and loss of faith in individual opinion. We are all in danger of developing into the type of person who has been described as "knowing the price of everything and the value of nothing."

I have spoken of the prosperity of the electrical industry—I think a better word would be "advancement." Advancement does not necessarily denote prosperity; it has always to be paid for, and the era of high wages and large profits can hardly be said to have arrived. The early half of the nineteenth century was, through the introduction of steam power, a period of enormous advancement in manufacturing, but it was anything but a prosperous one to the worker. Moreover, we are faced with severe competition, and competition always means cut prices from older interests. That this is becoming more intense is evident by the campaign in the Press, designed to single out and advertise the weak spots in our armour. We are aware that we have more fields to conquer and that we cannot always compete with raw and semi-raw fuels but, confident in the knowledge that our product in use is the most convenient, adaptable and healthful, and therefore the most scientific, we have nothing to fear.

The question of the nationalization of the electric supply industry has recently appeared on the political horizon. We are all familiar with nationalization in actual working, but at the present time the question is confused with so many crude theories of ownership, of the means of production and industrial control, that it cannot be said that public opinion is ripe for legislation of this character. In any case no industry can be said to be ready for nationalization until it is prepared as a whole to accept all the obligations of national service.

NORTH-EASTERN CENTRE: CHAIRMAN'S ADDRESS

By W. T. MACCALL, Member.

"ITEMS OF INTEREST, AND INSTRUCTION."

(ABSTRACT *of Address delivered at* NEWCASTLE, *27th October,* 1924.)

(I). GENERAL.

ELECTION OF COUNCIL.

Owing to well-known objections to the former method of election of the Council of the Institution a new scheme is in operation, but it has its drawbacks. Members will be more reluctant than in the past to make independent nominations, as is evidenced by the fact that last session was the only one of the last five or more in which no such nomination was made. The apparent reasons are, first, that such nominations seem now more like a vote of censure on the Council, and, secondly, that the probability of the election of an independent candidate is smaller than before. The dangers are that election to the Council will be restricted to those members who are known to the Council, and that ordinary members, having merely a formal part in the election, will lose interest in the composition of the Council. This will lead to dissatisfaction and possibly to loss of membership.

An improvement would be to retain the present method of nomination and to change the method of election to that of proportional representation by the single transferable vote. This would enable any section consisting of about one-sixth of the voters to secure the election of a particular member, and would ensure the fairest possible result in any contested election. Further, it would increase the number of voters. At present many are deterred from voting because they do not know a sufficient number of the candidates. Under proportional representation the voter may limit the expression of his preferences to the candidates he knows well; and this neither wastes his vote nor gives him any advantage over a voter who expresses a wider choice.

Those not acquainted with proportional representation may suppose that it is very complicated; but this is not the case. The method of counting the votes is certainly a little more complicated than the present system, but anyone can easily understand and carry out the counting after a quarter of an hour's instruction.

POWER SUPPLY.

A somewhat disquieting event of the past few months is that electrical power supply has become politically popular. This is to the good if it leads to more rapid development; but I trust that electrical power in reality, like foreign policy in theory, will remain outside party strife. Otherwise, electrical development will be retarded while politicians wrangle about some subject which should be left to electrical engineers.

Among events of particular interest to this Centre was the permission granted by the Electricity Commissioners to the Newcastle Electric Supply Co. to earth their system at several points. This was done after tests by engineers of the Post Office and of the power company in co-operation had shown that no harmful effects followed, provided that the earthed points were on the primary windings of transformers with delta-connected secondaries.

The raising of the line pressure for underground networks from 22 kV to 33 kV is being tackled by British mains engineers with little guidance from outside sources. The present methods of jointing appear scarcely adequate for the increased stress. It is evident that either now, or before the next rise in pressure is carried out, a radical improvement is essential in either the materials or the art of jointing.

The manufacture of the cables presents no special difficulty, nor is the pressure yet high enough to make intersheaths or similar schemes commercially advantageous; but it cannot be far in the future before methods of this type will require very serious consideration. It is therefore very unfortunate that our knowledge as to the conditions determining the breakdown pressure of a cable is extremely uncertain. It would be easy to devise experiments which would throw considerable light on this obscure region at a cost which would be small in comparison with its importance. I suggest that the Institution should co-operate with the cable makers and set up a Committee on the lines of the Buried Cables Research Committee, to investigate the criterion determining breakdown in high-pressure cables. The main points suggested for investigation are:—

(i) Is the criterion of breakdown in cables

(*a*) the maximum dielectric stress (voltage gradient);
(*b*) the dielectric stress at a radius $0 \cdot 368$ ($= 1/\epsilon$) of the outer radius of the insulation;
(*c*) the loss due to dielectric hysteresis;
(*d*) a combination of two of these;
(*e*) some other cause?

(ii) If the cause is found to be (*c*), (*d*) or (*e*) above, do the methods of construction and laying of cables which assist the dissipation of heat increase the breakdown voltage as well as the carrying capacity of the cables?

It can be shown mathematically, by making certain reasonable assumptions, that the dielectric-leakage loss on reaching a certain point will increase without limit and so must cause breakdown; and further that, whereas the heat conductivity of the dielectric largely

affects this critical point, alteration in the facilities for dissipating heat outside the dielectric affect the critical point only indirectly, and probably to a very small degree. But the assumptions, however reasonable, are insufficient as a basis for design until checked by experiment, as is shown by Preece's so-called "law" for fuses, which is based on mathematical proof from reasonable assumptions, but is inaccurate in fact. And the alternative rule for fuses ($I \propto d^{5/4}$) proved mathematically by Dr. Alexander Russell, though closer to the facts in many cases, requires considerable modification to bring it into good accord. Mathematical reasoning, on the other hand, does provide a basis for experiments designed either to confirm or to confute the assumptions on which it is based.

Has not the development of power supply arrived at the stage for the general use of the terms "megawatt" and the "megawatt-hour"? Magnetic flux is sometimes stated in megalines, and all are familiar with the megohm; then surely it is better to speak of turbo-alternators as of 20 megawatts (or MW) than as of 20 000 kilowatts (or kW), and of a daily output as, say, 583 megawatt-hours (MWh), rather than as 583 000 kilowatt-hours (kWh). Apart from the saving of time and space, there is a further advantage in the fact that it lessens the temptation of stating the latter quantity as, say, 583 172 kWh, although anyone at all familiar with metering knows that the last three figures are meaningless.

Ex-Enemy Candidates for Membership.

Another suggestion—about the present reception of which I have greater doubts, though not as to its ultimate consideration—is that the time has arrived for the withdrawal of the prohibition of membership of the Institution in the case of all citizens of ex-enemy states. I do not suggest that all such should be admitted on their electrical engineering qualifications without any regard to their nationality, but that it should be within the discretion of the Council to recommend them for election in suitable cases. In favour of this step I urge that "one cannot indict a nation," and however strongly one holds that some Germans, Austrians, Bulgarians or Turks were guilty of the terrible suffering and loss due to the war, it is un-English to penalize all members of those nations for all time. In this connection, it is relevant to point out that many who were citizens of the ex-enemy nations are no longer so, owing to changes in the frontiers. Of two electrical engineers living a few miles apart and of exactly similar antecedents one may, owing to a frontier intervening, be eligible for membership and the other ineligible under the present rule.

Tariff Dependent on Power Factor.

Arnò proposed a tariff for the encouragement of high power factors by charging on the "complex load" (defined as two-thirds of the kilowatt-hours plus one-third of the kilovolt-ampere-hours). By adjustment of the phase difference in an energy meter this "complex load" can be measured with reasonable accuracy over a fair range of power factors. My suggestion is that this method be used, since it requires no addition to the usual meters, but that the term "complex load" be omitted in the statement of the tariff. It would still have its use in deciding on the phase difference. The tariff could then be stated as in the following example:—

Charge at a power factor of 0·7 to be *n* pence per kWh.
Bonus for power factor of 0·8 to be 4 per cent.
Bonus for power factor of 0·9 to be 9 per cent.
Bonus for power factor of unity to be 15 per cent.
Penalty for power factor of 0·6 to be 5 per cent.
Penalty for power factor of 0·5 to be 11 per cent.

All these bonuses and penalties would require no calculation beyond multiplying the reading by *n* pence, the meter automatically changing its registration according to the power factor. The values of the percentages could be altered by changing the phase difference in the meter. The standard power factor at which the meter registers true kilowatt-hours could be altered by changing its gearing. The testing of the meters would be rather more difficult than with the standard pattern, but not seriously so.

The main obstacle appears to be the doubt as to the legality of basing charges on the reading of a meter of this type. The Electricity (Supply) Act of 1922, however, enables supply authorities to apply for sanction to be given to other methods of charging than those now allowed.

(II). INSTRUCTION.

Definitions.

This section might be termed "Education," but "Instruction" has been preferred as being wider in some ways though narrower in others. The Education Committee of the British Electrical and Allied Manufacturers' Association in their Report published in 1920 define "education" as "individual development through intellectual, moral, and physical instruction," and say that "the word 'training' is limited in sense strictly to practical instruction in the shops." "Instruction" therefore covers both education and training.

It is of some importance to define the terms used. The word "training" is used in a wider sense than the B.E.A.M.A. Committee's definition; in fact it covers even more than "instruction," by the inclusion of such things as the parts of collegiate life outside definite instruction. If I do not adhere to the meaning stated, I shall err in good company. For in the B.E.A.M.A. Report two lines below the definition of "training" this word is used in its wider, more general, sense.

The diversity of the methods of instruction in actual operation is due in a large measure to the diverse results desired in the finished product. The B.E.A.M.A. Committee's Report divides apprentices into four classes, viz.:—

(*a*) Trade apprentices, who will become skilled workmen, foremen, etc.;
(*b*) Engineering apprentices, who are trained for the drawing office, test-room, etc.;
(*d*) Student apprentices, who are trained for senior positions in the drawing office, etc.; and
(*d*) Research apprentices.

These definitions should be borne in mind in connection with quotations from this Report, which is a very valuable piece of work, but would have been even more so if the Committee had included a full-time technical (as distinct from university) teacher.

Preliminary Training.

Up to about 11 years old the choice lies between the (public) elementary school and a private school. I consider that for engineers the greater advantages are with the former. These consist in making the acquaintance of boys of a great variety of types, and in the (usually) more efficient "instruction"; while those of the private school are the socially higher class of the boys, and the (doubtfully) better "education." There is much to be said for the general Scotch and American practice of common elementary schools for all classes.

received a college training, the figures for England being:—

Year	Men	Women	Total
	Per cent	Per cent	Per cent
1913–14	74	54	60½
1919–20	75½	62	66
1921–22	78	65½	69

At the age of about 11 years the majority of the private school pupils will pass to a secondary school (see Fig. 1). This will also receive pupils from the elementary school, some by means of scholarships (known as "free places"), others paying the ordinary fees. The bulk of the elementary school pupils will continue therein until 14 years of age or a little over.

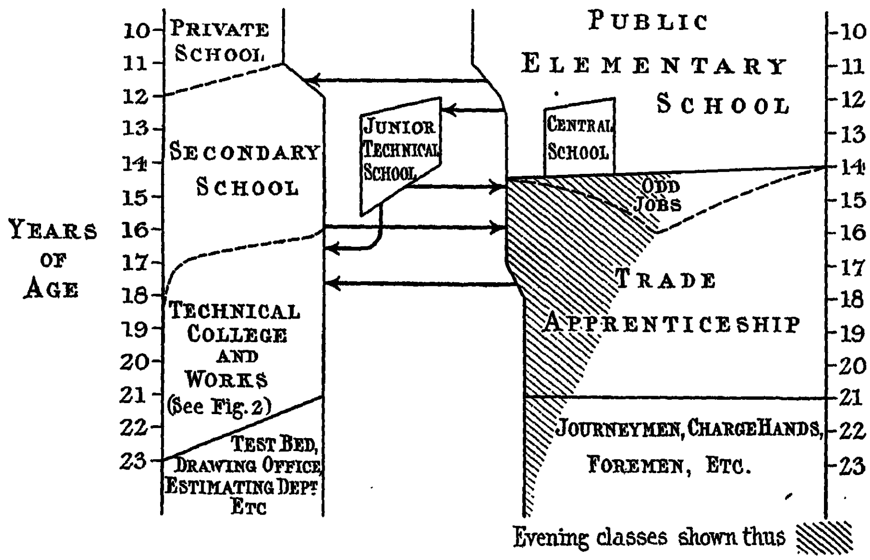


Fig. 1.

As regards trade apprentices, the following quotation from the B.E.A.M.A. Report gives the main point; others occur incidentally. "The general education of trade apprentices should consist in an equilibrium between intellectual studies and practical activities (including organized games) so arranged as to encourage the growth of civic and social ideals. It should not be specialized with respect to practical studies, trades or hobbies, but should be directed towards the development of human beings of character and intelligence. In choosing subjects . . . those might be selected which will enable a sound foundation to be laid for subsequent vocational training."

The Report refers also to the insufficient training of teachers. This is being gradually improved, the percentage of certificated teachers out of the total of about 150 000 in public elementary schools in England having increased from 68 per cent in 1913–14 to 71 per cent in 1919–20, and to 72½ per cent in 1921–2. Moreover, an increasing percentage of these certificated teachers has

Fig. 1 does not attempt to show the percentage taking secondary education, but the following figures for all boys will give a probable percentage for budding electrical engineers. In 1922, in England, there were 543 149 boys between the ages of 12 and 14 in elementary schools, and about 129 000 between the ages of 12 and 16 in secondary schools. There was therefore about 11 per cent of the total in secondary schools. Of those leaving the elementary school at 14 years of age most will start their trade apprenticeship at once or after a period as errand boys, etc. Their other source of training will be in evening and correspondence classes. A few will have a longer schooling through transferring at about the age of 12 to a junior technical school, and still fewer by entering a secondary school.

There are great differences of opinion as to what the work of the junior technical school should be, and also large differences in the actual work of existing schools. For the moment it is sufficient to say that a junior technical school is not a trade school, and is something

between that and a secondary school with a technical bias.

The junior technical school course lasts two or three years. On its conclusion the majority of pupils will become apprenticed and complete their training in evening classes. The expectation (which is confirmed by experience) is that the pupils of the school will, before the end of apprenticeship, usually outstrip those from elementary schools. The former will thus qualify for positions requiring greater technical knowledge or entailing more responsibility. The best of the junior technical school pupils should be able to obtain and to profit by training of a higher type.

Nearly all the secondary school pupils take some form of higher training, but a few become apprentices and receive only evening-class instruction. On the other hand, a few of those apprenticed soon after leaving an elementary school will succeed later in obtaining higher training inclusive of day classes.

These various courses are indicated by the arrows in Fig. 1. There are, however, two main streams, viz. :—

(a) Elementary school followed by (trade) apprenticeship accompanied by evening classes;

(b) Secondary school followed by technical training, at least partially in day classes.

Higher Training.

Methods of day-class training may be divided into two main groups :—

(I) Those in which the whole of the academic instruction is given continuously (apart from vacations), the course covering three years normally;

(II) "Sandwich" systems, in which the academic and workshop parts of the instruction occur alternately.

Fig. 2, I (a), (b), (c), shows the subdivisions of group I according to when the three years' academic course is taken. I (c) combines most of the advantages of the other two, and so is superior to either of them. This opinion was supported by the Institution of Civil Engineers and by the B.E.A.M.A. Committee. They say: 'It is becoming increasingly customary for boys to have a year's experience of a suitable training course in a Works before proceeding to a university. This enables each boy to find out where his interests lie, and it establishes a connection between the youth and the Works which may subsequently be mutually advantageous. After such a period the college course is followed much more intelligently."

The sandwich systems also have three subdivisions [see Fig. 2 II (a), (b), (c)] according as the length of the continuous period of academic instruction is :—

(a) a year; (b) five or six months; (c) a few hours.

(a) This is the Faraday House scheme, a four years' course with the first and third years in works, and the second and fourth years at college. The students have usually stayed longer at school so as to cover the mathematics, physics, etc., of the more usual courses.

(b) In this there is a preliminary year or more in works, followed by four (sometimes less) years of which part is spent at college, the rest in works. Examples are the Sunderland Technical College with four 6-month periods (October to March); Rutherford College, Newcastle-upon-Tyne, with three or four 5-month periods; Sheffield University, with 2-year and 3-year courses; and for railway engineers, Darlington Technical College (5 months); and for mining engineers, Treforest School of Mines (6 months).

(c) In this from 3 hours to 12 hours (normally 8 hours) per week are spent in day classes, combined with evening classes on two or three evenings a week. This type of course is often carried out in works schools, but also in technical schools, e.g. the Woolwich Arsenal Trade Lads scheme. It is usually of the trade-apprenticeship type, i.e. a modified evening course rather than a sandwich day-course.

Another course which may be considered to belong to this group is that in which the college supplies all the practical instruction, as well as the technical part, and possesses workshops run on commercial lines. This system is attractive at first sight but has many draw-

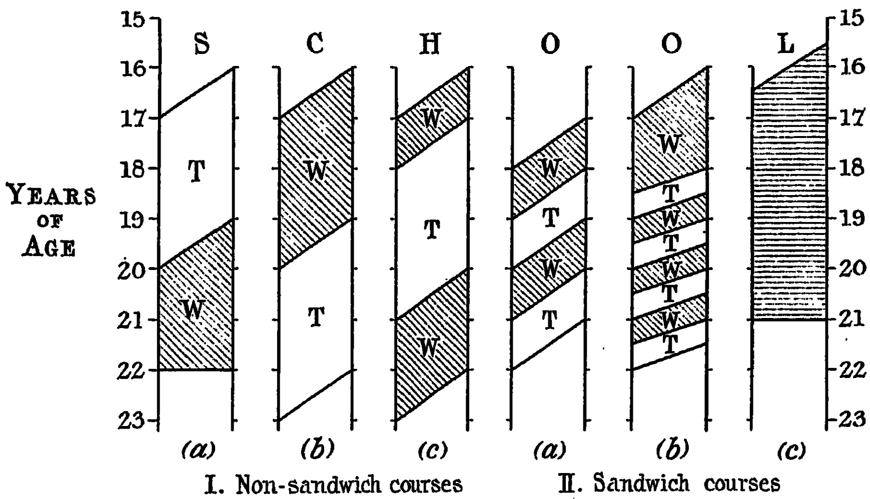


Fig. 2.—Courses of technical instruction. T = technical college; W = works.

backs, e.g. the difficulty of keeping equipment up-to-date and the working really commercial; and the natural objection of the owners of works to the subsidized competition of the college.

The advantages of the sandwich system are that the alternation of the two types of training increases the value of each of them. The workshop training makes the college work more interesting to average students. On the other hand the college instruction shows the reasons for many workshop practices. The disadvantages for the students lie in the tendency to attempt too much in the time available. The best length for these periods depends partly on the capacity of the students, partly on the rapidity with which they can adapt themselves to the changes in the type of instruction (college and workshop), and partly on the suitability of the periods for the workshop organization. As far as the first two are concerned, my preference is for type II (*b*).

Just as there is excessive leakage in a transformer if the windings are not sandwiched, so there is a loss of benefit in a course in which the whole of the college instruction is concentrated into three successive years. Sandwiching diminishes magnetic leakage, and similarly improves the course of instruction by making closer the interaction between the academic and workshop portions (I refrain from particularizing as to which of these two corresponds to the "primary" and which to the 'secondary" of the transformer). Again, the greater the extent of the sandwiching the greater the reduction of magnetic leakage, but if this is carried too far there is excessive loss of winding space and increase of cost due to the additional insulation needed. This corresponds to the loss occurring in courses of instruction in which sandwiching is carried too far, due to the time needed for adaptation when changing from one type to the other (college to workshop and vice versa). Whether six months is the optimum length for college periods is a matter of opinion, but I have little doubt that it is close to the best value.

That technical teachers are in favour of the sandwich system is shown by the unanimous passing at the 1924 Annual Conference of the Association of Teachers in Technical Institutions of the following resolution: "That this Conference, considering the need for extended technical training in the development of industrial processes, desires to express its conviction that immediate steps should be taken to develop and extend sandwich systems of training for boys preparing for industrial careers, and urges local education authorities and Industrial Organizations to co-operate in providing the facilities required for joint technical and industrial training."

Curriculum.

Early training is almost necessarily general, specialization amounting only to the difference between the classical and "modern" sides of a public school. Even when greater specialization is possible it would not be desirable to make the training of engineers different from that of non-engineers at this stage.

The case of Oundle School is not really an exception to this statement. In its equipment are included metal and wood workshops, an engineering laboratory with gas, oil and steam engines and a turbine, pattern-makers' shop, forge, foundry, and a metallurgical laboratory. It contains, however, in addition a biological laboratory, two farms, one purely experimental of over 30 acres, the other of about 100 acres, and gardens, and also the usual laboratories. This equipment was not obtained for the purpose of producing skilled engineers or biologists or farmers, but to give each boy the fullest opportunity for development.

A very brief summary (largely in his own words) follows of the aims of F. W. Sanderson who established Oundle in its present form.

Boys at about 15 begin science with an informal, mainly experimental, course to learn "to do things and to take pleasure in this." First, applied mechanics; later, chemistry, biology, or geology. Next year, pure physics and mechanics are introduced similarly, and then a more regular course of applied science. In heat the steam and gas engines form the basis of instruction.

In the workshops Sanderson insisted that boys come to school "not to learn but to do." They were to be "the home of creativeness." Their primary object was to give the boys the opportunity to do constructive work for the community, not exercises devised for instruction. The operations inculcate accuracy and attention, in place of teaching these by courses of practical measurement. The workshops and laboratories are open to the boys out of school hours.

"Applied science is complex and apparently difficult, yet it has romance and mystery which appeal to youth." Moreover, "it is in direct contact with the ordinary life of the day." Again, "Science teaching must be alive, changing, moving forward. It should not have about it the atmosphere of certainty and finality."

And in his last lecture, at the end of which he died suddenly: "It is not difficult to see that a modern school is not created by abandoning ancient studies. Far from it. Nor by converting it into a technical school. If these alone are the changes made, the soil will remain much as it was. . . . A modern school is a school in which the spirit which we call the spirit of science permeates and changes all its methods, aims, and relative values. Such a school will endeavour to make the fullest use of all branches of knowledge and of all the faculties of all its members. It will have constantly in mind the welfare and development of all its workers; and its aim will be to do service for the community.

"The school will therefore have . . . a wealth of plant, apparatus, and opportunities for community work. . . . The usual school studies are really the tools, and class-rooms the tool-making shops, all directed towards the main purpose of the creative factory. It will soon be evident that methods of teaching are of very slight importance compared with the overwhelming urge to create and to do service and to master the necessary tools and their use. . . . We must send out workers imbued with the determination to seek and investigate truth—truth that will make them free—and to take great care that in the search for truth they will never take part in or sympathize with those methods by which the edge of truth is blunted."

There is the ideal; but let us consider the present state of things.

Most students entering an electrical engineering course from secondary schools have had an education including (i) a general English course; (ii) Latin, and possibly some Greek; (iii) French or German, possibly both; (iv) mathematics; (v) mechanics; (vi) geometrical drawing, and sometimes engineering drawing, but not design; (vii) chemistry; (viii) physics; (ix) manual training, usually woodwork; (x) physical training, including organized games.

The above is a bare skeleton on which may be built courses differing as widely as the members of the human race. Similarly the actual courses in British schools, though they have some family likeness, differ somewhat as the varied members of the British race. This variation lies partly in the relative amounts of time given to the different subjects, and partly in the spirit and standpoint of their treatment.

The B.E.A.M.A. Committee's recommendation on this point for engineering apprentices is merely "that boys who propose to enter the engineering industry should give special attention to the study of mathematics and science." This will be provided by any secondary school, and does not require a specifically engineering type of instruction; as is emphasized by the Committee in saying "Education obtained in those schools providing an engineering side cannot be accepted in lieu either of the practical training of the works or of higher technical training." And later, "The best foundation for any grade of industrial life is sound general education, entirely free from specialization in any form."

There will be no difference of opinion as to many of the subjects to be included in day courses, though there may be as to the amount of time to be given to them. These include (*a*) mathematics; (*b*) engineering drawing and design; (*c*) applied mechanics, merging into strength of materials, and structures; (*d*) physics, merging into electrical engineering, with the possible addition of heat engines; (*e*) chemistry, with an engineering bias.

These subjects with laboratory work occur in all electrical engineering courses, but the time given to them varies largely. Taking three B.Sc. courses at random the relative times are:—

Group.	Course A.	Course B.	Course C.
Mathematics and mechanics	$18\frac{1}{2}$	23	$27\frac{1}{4}$
Mechanical engineering	$20\frac{1}{2}$	20	25
Electrical engineering	30	31	24
Physics	9	$6\frac{1}{2}$	$9\frac{1}{4}$
Chemistry	5	$9\frac{1}{2}$	3
Languages	7	nil	$1\frac{1}{2}$

The figures are not percentages but total 90 for each course, corresponding to three sessions with 30 hours' work per week.

It would be easy to draw up a complete course including nothing but the subjects (*a*) to (*e*), which would give a reasonably varied training. Actual courses, however, include other subjects, e.g. hydraulics, German, estimating (or other commercial subject), industrial management, etc. Everyone agrees that a knowledge of these other subjects is useful; but the following facts must be considered:—

(1) Instruction, including laboratory and drawing classes, lasts for about 30 hours a week for three or four years.

(2) "Electrical engineering" alone, apart from design, is really several subjects, not one.

(3) Students are human.

What can be done to overcome these obstacles to the inclusion of additional subjects?

(1) (*a*) "Increase the hours per week." This would be worse than the ill which it attempts to cure. Students reading for the Cambridge Mathematical Tripos say "Five + one = six; but six + one = five"; i.e. not more than six hours per day can be employed usefully in study. In an engineering course with its greater variety owing to laboratory work, etc., this allowance may be increased, but the same principle holds.

(*b*) "Increase the number of years in the course." More can be said in favour of this, but a longer course would increase the number debarred from a full-time course by lack of means. This can be mitigated by scholarships and by reducing the length of the works training. If this is organized with the aim of giving real training rather than of obtaining cheap labour, and if the student is keen to profit by his opportunities, this reduction can be made without losing the value of the works training. The B.E.A.M.A. Report recommends the reduction of this to two years for student apprentices who are graduates.

(*c*) "Cut down the time given to some of the present subjects." The usual complaint is that the present time available is insufficient for thorough treatment, and many consider that it would be better to concentrate on a smaller number of subjects. In some cases time for extra subjects could be obtained by allowing a greater variety of choice in the last year of the course. This must entail increased expense, which the result may not justify. It is perhaps worth pointing out that in any reasonable course of design considerable reference to costs will be included, and this may be amplified instead of attempting separate classes in costing.

Some of those who recommend these extra subjects are thinking too exclusively, it seems to me, of their own particular branch, and not of electrical engineering as a whole. I am not saying that any or all of the above subjects should be excluded, but am merely pointing out that their inclusion must be paid for, and that, as in most engineering problems, it is a question of so balancing advantages as to arrive at the best solution.

Mr. Dempster Smith, Head of the Department of Industrial Administration in the Manchester School of Technology, said (1924): "A careful examination of the course of study usually provided in technical colleges of university standing leads to the conclusion that nothing can be cut out without detracting from the training." And he suggests an additional year for "a liberal introduction to this most interesting subject (viz. industrial administration) which the student can develop while receiving his practical training."

The second obstacle, viz. the multiplicity of the branches of electrical engineering, introduces similar considerations. It can be dealt with partially by increased specialization. But a student by no means always knows into what branch he will go: and when

he thinks he knows, the future often falsifies his expectations.

The third obstacle, that students are human, could be overcome by replacing them by Robots. But these would not require any education, so this possibility need not be considered. On the contrary, I endorse strongly the statement of the B.E.A.M.A. Report that "It is desirable that all engineering students . . . should enter into the full collegiate life, as the experience thereby gained is of real advantage in an industrial career."

Suggestions for Improvement.

Education up to 12 years old appears to be developing on sound lines; but from 12 to 15 years of age there seems to be need for a great extension of junior technical schools. In 1921–2 there were in England only 86 of these, with a total attendance of 10 302 boys; and only 34 schools had 3-year courses. Their work is supplemented by "central schools," which, however, are merely elementary schools confined to the higher classes and are not technical.

Most of the 2-year junior technical school courses should be extended to 3 years, and these might be continued longer, up to 16 years old. Alternatively, the year 15–16 might be a part-time course so as to make less abrupt the transition from school to works. The junior technical schools should be allowed to have courses suitable for boys preparing for matriculation. Even when a secondary school exists in the same district, most elementary scholars will be unable to attend it unless they win scholarships when 12 years old. Those who develop late ought to be given in the third year of their junior technical school course another opportunity of obtaining higher education.

The chief defect in secondary education also seems to be that there is inadequate provision for the numbers who desire it and would profit thereby.

The main principle of these suggestions is to increase the lateral fluidity indicated by the arrows in Fig. 1. To quote the B.E.A.M.A. Report again, "Greater facilities must be afforded for selecting and training that limited percentage which will be engaged in directing the work of others, or in prosecuting work of a highly technical character. The ability to carry out such work is not confined to one section of the population."

Anything which widens the area of choice is good, e.g. (*a*) increased provision of secondary education and of "free places," supplemented by maintenance allowances; and (*b*) further scholarships to higher technical institutions from secondary and from junior technical schools, the latter being contingent on the suggested permission to junior technical schools to give matriculation work.

These may be summed up as "more, and more varied scholarships (including maintenance) at every stage, culminating in research scholarships"; but with the corollary "greater precautions to prevent the waste of costly instruction on unsuitable students."

For the workshop training is needed a further extension of the practice of many manufacturers in affording suitable courses in works, including in this the extension of the sandwich system. Even if the provisions of the Education Act (1918) for courses of type II (*c*) is brought into general operation, the need will still exist for more sandwich courses of the higher type.

TEES-SIDE SUB-CENTRE: CHAIRMAN'S ADDRESS

By A. M. Paton, B.A., B.Sc., Member.

"THE PROFESSIONAL STATUS OF THE ENGINEER."

(Abstract *of Address delivered at* Middlesbrough, *13th November*, 1924.)

On such an occasion as this, it is the custom for your Chairman to deliver a short address on a matter or matters of general interest, without dipping too deeply into technical matters. New developments on Tees-side, with which I am principally concerned, do not, I regret to say, constitute a promising subject for an address. Bad times are responsible for the holding-up of a considerable amount of projected new work. Directors and managers are occupied with the problem of keeping their existing plants loaded, and have postponed contemplated extensions until better times arrive. Lest, however, we may be inclined to take too short a view of the present position, I may be excused for mentioning some encouraging words spoken by an eminent man of this district at a function at which I happened to be present. They were to this effect: "The best thing that manufacturers on Tees-side can do under present conditions is to keep their heads: the natural advantages of Tees-side must tell in the long run." We all hope that it may be true.

In the circumstances, I propose to say a few words on a subject which affects each one of us, and which is particularly in our minds at the present time, namely, the professional status of the engineer in Great Britain.

As a preface to my remarks, I would put the fol-

lowing words, which I came across recently in an American technical journal:—

"It is difficult to appreciate the cycle through which engineering has passed in the last two decades. Twenty years ago it was a profession more or less mysterious to the general public. Its work was associated largely in their minds with the building of bridges and viaducts. Its members were not known professionally to the average citizen. The functions of the mechanical engineer could not be described by the average man. The combustion engineer was unknown. The electrical engineer was an inventor, the most renowned amongst them being termed a wizard. To-day the men of this calling present as a whole the most definite profession in public life. They are recognized as the men in whose hands the material advancement of the race rests. They have gained a leading, if not the leading, place in the list of professions."

The last part of this extract is the part which to me is the most striking. If it truly represents the status of the professional engineer in America, as I believe it does, I think that we must recognize that engineers are more honoured there than they are in this country. Later, I shall have a few words to say as to their actual status.

I propose now to examine briefly the status of the engineer in this country, to contrast it with the status in America and Canada, and to offer some reasons for that status and also some suggestions for helping to raise it to the status which I maintain it ought to occupy. By way of introduction to the subject, we may first consider the meaning of the word "engineer." The word was originally a military term, like "charioteer," "musketeer," etc., and denoted one who managed military engines or artillery. Later it has come to denote one who manages or has to do with the construction or use of engines or machinery, or a person skilled in the practice of engineering, that is, the construction or use of engines or machinery, or the art of executing such works as are the objects of civil and military architecture, in which machinery is extensively employed.

It appears, then, that the title "engineer" has always denoted a person with superior knowledge or skill, primarily in military works, but latterly also in civil—in contrast to military—works. We electrical engineers are concerned with the civil side of engineering only, hence all my remarks this evening are confined to civil—in contrast to military—engineering.

The original and classic definition of a civil engineer occurs in the Royal Charter of Incorporation of the Institution of Civil Engineers, granted in 1828, that institution being the first and only professional engineering institution in existence at that time. As the definition may not be familiar to some of you, it is worth noting . . . "the profession of a civil engineer, being the art of directing the great sources of power in nature for the use and convenience of man." It is curious that this definition might have been framed for the electrical engineer—then of course undreamed of—so aptly does it describe his present functions.

Notwithstanding the enormous development in engineering which has taken place during the last half-century, and the corresponding increase in scientific knowledge which the engineer has had to acquire as part of his equipment for his profession, the title "engineer" has in this country never become a term of art in the legal sense; that is to say, any person may describe himself as, or practise as, an engineer whatever his qualifications or experience. It is therefore not surprising that the title is of no repute in this country. [Mr. Paton read a few cuttings from recent newspapers in order to illustrate the current abuse of the title "engineer."]

We may well ask ourselves whether there is not something amiss in a community which classes men, obviously of the worst type, as members of the same profession as ourselves and others who have spent years in acquiring the necessary knowledge and experience. There can be only one answer to that question. The next question then follows: How long is the community going to allow such a state of things to continue? I hold, and it is the object of my remarks this evening to show, that we engineers in the true sense of the word must not be content until the title "engineer," or at any rate some simple modification such as "registered engineer" or "professional engineer," is so established by law that the community will regard it in the same way as they now regard the titles "registered medical practitioner," "solicitor," etc.

Next let us see what has been done in the desired direction. On the broadest lines which I have suggested as being desirable I do not know of anything having been even attempted, and it is only since the war that less ambitious attempts have been made. These have succeeded as far as they have gone. The first steps of the kind were taken in 1919 by the Institution of Civil Engineers, who proposed to introduce a Bill in Parliament reserving the title "civil engineer" to its corporate members and others coming within the scope of that title as defined in the charters of the Institution, and interpreted in their broadest sense. Under that Bill all "civil engineers" would have been registered, and only those so registered would have been entitled to describe themselves as "civil engineers." The objects of the Bill were, however, found to be unattainable, largely, I believe, to the title "civil engineer" being so broad as to affect other Institutions who considered themselves inadequately provided for. The Bill was therefore not proceeded with. In 1922 the same Institution obtained its second supplementary Royal Charter, leading to the establishment of the title "chartered civil engineer" for its corporate members in 1923. Similarly our Institution obtained its Royal Charter in 1921, and the similar title "chartered electrical engineer." As I understand the wording of the bye-laws governing the use of these titles, the title must in every case be preceded by a designation of the class in the Institution to which the user belongs. In other words, it is not in order to use the title "chartered electrical engineer" without the preceding letters M.I.E.E. or A.M.I.E.E., as the case may be. These somewhat

cumbrous titles then may be taken to indicate the present difficulty of establishing such simpler titles as "civil engineer" or "electrical engineer." So far as I am aware, these are the only steps of the kind which have been taken in this country.

The Institution of Mechanical Engineers has not yet proceeded on similar lines, because it is of opinion that the principal advantage of a Charter is one of sentiment, and is balanced by the cost and the difficulty that arises if variation of the constitution or bye-laws should be required. This view appears to support my own, that although the recent achievements constitute a big advance in the right direction they are not to be regarded as final.

Next it is interesting to compare the legal status of chartered engineers (in which term I include chartered civil engineers and chartered electrical engineers, for simplicity) with that of the members of other professions. These professions which are at all comparable with our own appear to me to fall into two classes. The first of these includes the older professions, of which the medical practitioner and the solicitor are typical; and the second the newer professions, of which I regard chartered patent agents, architects and surveyors, accountants and secretaries as typical.

Acts of Parliament provide for the control of the older professions, and for the registration of all persons qualified to practise. In addition, the solicitor has to provide himself annually with a certificate entitling him to practise. These Acts provide fines in the case of any person falsely pretending to be qualified or registered. Thus falsely to pretend is therefore a criminal offence which can immediately be stopped. A qualified but unregistered medical practitioner may practise, but cannot recover by legal process any fees, nor hold an official appointment, nor sign any certificate required by Act of Parliament. To all intents and purposes, therefore, registration is necessary for the purpose of practice.

Chartered engineers are of course not regulated by Act of Parliament, and have not any legal advantage over any other person in respect to the recovery of fees, the holding of official appointments, or on any other material point. Further, it would appear that, if any person were falsely to pretend to be a chartered engineer, that would be a civil and not a criminal offence. To stop this, the Institution concerned would apparently have to apply for an injunction in restraint of the wrongful use of the title reserved to its members. This would be a complicated process in comparison with the simple recovery of a fine instituted by Act of Parliament.

In trying to assess the relative necessity for the legal establishment of the medical and the engineering professions, it might be argued that the medical is the more necessary of the two because the work of a medical man may often affect the life of his patient. This is a very strong argument. To meet it I could only suggest that a mistake on the part of the chartered engineer might have more serious consequences to life than that of the medical man. The former might involve the loss of many lives—take, for instance, a wrongly designed flywheel or bridge—whereas the latter as a rule involves only one life. On the whole, there is no getting away from the fact that medical registration is a very necessary procedure for the protection of the public.

The case of the solicitor differs from that of the medical man and the engineer in that the practice of his profession does not involve any danger to life. On considering the arguments, I have not been able to find one leading to the conclusion that the registration of solicitors is more necessary than that of chartered engineers.

Since registration is a necessary procedure in the control of a profession by Act of Parliament, I may perhaps explain the mechanism of medical registration. This is in the hands of the General Council of Medical Education and Registration established by Act of Parliament in 1858 in order to secure a minimum uniform standard of qualification amongst medical practitioners trained at different places. It consists of representatives elected by the training bodies, the Crown and the medical profession. Any person possessing the necessary qualifications is entitled to be registered by the Council on payment of the prescribed fee. Once a year the Registrar of the Council is required to publish a list of the names on the Register, as those entitled to practise. The Council deals with all cases affecting professional conduct.

We chartered engineers must recognize that the measures which I have outlined have been singularly successful in the case of the medical profession, and the principal factor in guiding that profession into the high position of efficiency and esteem which it now occupies.

Apart from the advantages which members of the older professions enjoy in respect of their practice, they are not required to serve on juries. There seems some ground for this in the case of medical men, but none in the case of solicitors. Legal luminaries so often descant upon the privilege of serving one's country as a juryman that it is surprising the legal profession do not set others the example in this respect. In this matter of public service I am sure that chartered engineers are willing, however inconvenient it may be to them, to do their duty.

The only one of the newer professions on which I have to make any comment as being on a different status from our own is that of patent agent. This profession is established by Act of Parliament on similar lines to the older professions. This case seems to me to create a hopeful precedent for engineers, which I need not trouble to elaborate.

I trust that by the foregoing examples and remarks I have established the case for the ultimate control of our profession by Act of Parliament on similar lines to the others I have cited. That such legislation is not an idle theory, and that without it we are lagging behind other countries, I hope to show by outlining what has been done in Canada and the United States in this respect. [Mr. Paton then read extracts from Acts passed in 1920 in the provinces of Alberta and British Columbia and also similar legislation in the United States to establish the engineering profession.]

I now pass on to suggest a few reasons for the

existing status of the engineer, and to offer a few suggestions to influence us in our efforts to obtain our rightful status. The reasons which I would suggest fall into two groups :—

1. Those without the control of the engineering profession ; and
2. Those within that control.

In the first group I put the following reasons :—

(a) Natural conservatism of the British public.
(b) Ignorance of the Government, the administrative classes, and the general public on scientific matters.
(c) Lack of tradition in the engineering profession.

In the second group I put the following reasons :—

(a) Apathy of the engineering profession.
(b) Lack of unison amongst the engineering profession.
(c) Insufficient participation by the engineering profession in public affairs.

1(a). *Natural conservatism of the British public.*—In endeavouring to account for the existing status of the engineering profession, I have come to the conclusion that the natural conservatism of the British public is one of the factors which have had a retarding effect upon that status. This conservatism acquiesces in the conditions of the past and refuses to adapt itself to new conditions.

I think it unquestionable that the British public has not yet taken the trouble to recognize that there is such a thing as a profession of engineering, and will not do so until compelled by force of circumstances. As an instance of that conservatism, there has in the past been a feeling amongst the leading families in the country that to be connected with trade is *infra dig*. Since engineering cannot be practised apart from trade, that to some extent comes under the same category. There could not, of course, be anything more false or injurious, because trade is the life-blood of the country, and everybody in it is, to a greater or less extent, dependent upon trade. Nevertheless, the feeling which I have indicated has tended to prejudice the status of the engineer by directing a steady flow of recruits from those families into the church, the army and navy, law, medicine and the civil services in preference to engineering. In these circumstances it is not surprising that the status of the engineer is not so high as it ought to be.

Having classed the conservatism of the public as a reason beyond the control of the engineering profession, naturally I can suggest no remedy beyond the lapse of time. I think, however, that each individual engineer can do a little to help matters. In the first place, he can by his personal example show the general public that he is a man of high culture and ideals. In the second place, he can use his influence to induce the best young men, in every sense of the word, to enter his profession.

1(b). *Ignorance of the Government, the administrative classes and the general public on scientific matters.*—Arising to some extent out of the conservatism of the British public, I now come to probably the most vital reason, which is the ignorance of the Government, the administrative classes and the general public on scientific matters. Governments have recently arisen and fallen with such rapidity that it has been difficult to keep track of their individual members. It is, however, a fact that a few years ago there had only been one trained scientific man in the British Cabinet for the previous 100 years.

The administrative officials of the country have been for the most part appointed by examinations in which science has played an almost insignificant part. Consequently the public and other schools of the country have been accustomed to frame their curricula to suit the examinations, almost to the exclusion of scientific subjects. Hence it has come about that recently 34 out of 35 leading public schools had classical men as headmasters, and not one a scientific man. In these circumstances it is only to be expected that the officials and civil servants recruited from these schools have little knowledge of, or sympathy with, scientific matters of any kind, not to mention the scientific profession of engineering. If there were any doubt on this point, which I think there cannot be, reference to the periodical honours lists issued by the Government of the day will show the relative value placed upon the public services of the engineer in comparison with those of the navy, army, administrative, civil and diplomatic services.

Here, again, is a state of affairs which only time and increasing knowledge and appreciation of modern conditions can cure. I think that knowledge must inevitably come quickly, for, if this highly organized and densely populated country is to continue to occupy its present position amongst the nations of the world, it can only do so by conducting all its affairs on a truly scientific basis. Once this fact is thoroughly recognized we may perhaps see the inauguration of a Ministry of Science, leading to a gradual improvement in the status of all scientific workers, including all members of the engineering profession.

Before leaving this point it is gratifying to note that the nation is, in spite of its Governments and officials, becoming more and more scientific from day to day. The advent of the motor cycle and motor car have done a great deal to spread a knowledge of mechanical engineering amongst the general public, and the popular craze for wireless transmission during the last two years has turned everybody into an amateur electrical engineer.

1(c). *Lack of tradition.*—Although real, tradition is a subtle thing, wherefore I shall not say anything about it. I do, however, feel that our profession is of such comparative recent growth that it suffers in status by the lack of the fine traditions of service which obtain in the older professions. In this connection we can but endeavour to initiate and hand down a standard of honour and service fully equal to that obtaining in the older professions.

2(a). *Apathy of the engineering profession.*—I must reluctantly assign the foremost place amongst the reasons within the control of the engineer to his own apathy. Although it is obvious that the individual engineer is powerless to improve his status, and that

this can only be done by combination, there are nevertheless many engineers, some of them in good positions, who neglect, or do not consider it worth their while, to associate themselves professionally with their fellows. Personally, I recently met one such man, who seemed proud of the fact that he had stopped his subscriptions to several engineering institutions as soon as he became prosperous.

As far as I can see, the only bodies in the country which are sufficiently strong and representative to carry any weight in a national matter, such as the further improvement of status, are the three great Institutions in London, of which we are the largest. It is therefore the first duty of every qualified engineer, whatever local institutions he may support, to belong to at least one of these three Institutions. It is incumbent upon members of Institutions, in the words of their undertaking on election, "to advance the objects of the Institution as far as is in their power." It is incumbent upon the Institution as a body to keep in touch with developments in all other countries affecting the status of their engineers, and with public opinion in this country, and to see that this country is not in any way behind others in this respect.

2(*b*). *Lack of unison amongst the engineering profession.*—It is, I think, unfortunate for the status of the engineer that the interests of his profession are in the hands of not one body, but three, not to mention a host of smaller ones. It is, I think, still more unfortunate that in the matter of status each body has seen fit to act, or not to act, as the case may be, independently of the others. This gives the impression to the general public, which is no doubt correct, that we cannot agree amongst ourselves as to the status we want. For that reason I should welcome immediate co-operation between the Institutions in this and all other matters affecting the profession as a whole. It would, I suggest, be a good thing for the profession to form a small "General Engineering Council," consisting of a few members from each Institution, to deal with all matters of the kind.* In the course of time this Council would no doubt expand into a Council fulfilling the same functions, as nearly as may be, as the General Medical Council.

It is interesting to note that combination of the members of the three Institutions would bring into line a body of members approximately half the number now on the medical register, which latter is about 48 000.

2(*c*). *Insufficient participation in public affairs by members of the engineering profession.*—The small extent in which we engineers participate in public affairs is to my mind another reason for our present status. We are, I fear, out of the eyes of the general public, and "out of sight is out of mind." Unfortunately, the average engineer has little time to devote to public affairs after finishing his daily work and his constant struggle to keep himself up-to-date by absorbing a fractional part of the technical literature which is such a feature of these times. Therefore I suggest that large employers should take the long view and allow some of their suitable men time to participate in public affairs. At the last two parliamentary elections we have seen the managing director of one of the largest electrical manufacturing companies standing as a candidate. That precedent is one which I suggest might be extended to employees of good standing, and also to municipal and other public affairs. If this suggestion were adopted, wherever possible, I feel sure that the time so allowed would come back to the employer, with interest.

Under a previous heading I have suggested that it is a necessity for this country to conduct all its affairs on a scientific basis. To carry that out the country requires more engineers in Parliament. To see that they get there is therefore an important duty of the engineering profession, both for the prestige of the profession and the good work they can do for the country.

In conclusion, I should like to explain that I do not advocate change of status for the mere sake of change, nor for the sake of putting our profession on the same legal status I have mentioned; but because I believe that the change would lead to our better standing in the community and an increase in our prosperity.

If I have succeeded in convincing you that we have not reached finality in this matter of our status, my address will have served its purpose.

* ADDENDUM. The Engineering Joint Council (see *Journal I.E.E.*, 1924, vol. 62, p. 533) appears to fulfil many of the functions of the General Engineering Council referred to in this Address.

DIRECTIONS FOR THE STUDY OF UNVARNISHED* TEXTILE FABRICS (INCLUDING CLOTH, TAPE, WEBBING AND YARN).†

[REPORT (REF. A/S11) RECEIVED FROM THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION.]

CONTENTS.

* The term "unvarnished" denotes that the fabric has not been varnished or impregnated with insulating compounds, but embraces material which has been subjected to treatments such as those referred to in this Specification.

† The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

PREFACE.

Varnished cloth being a complicated material with many variables affecting the final product, it was considered necessary, with a view to the improvement of this class of insulating material, to attack the problem in detail.

Work on raw fabrics has now reached such a stage that the Association is able to issue directions for the study of suitable types for the manufacture of varnished cloth, and also for the study of the properties of unvarnished tape and webbing, which are employed

in the construction of electrical machinery and apparatus.

In view of the confusion existing in the terminology adopted in the cotton and kindred industries, it was considered desirable to deal with this subject somewhat fully. All the processes likely to be employed in the manufacture of cotton and linen fabrics for electrical purposes have been defined, and some information is given with respect to silk. The last named material, however, has not been dealt with exhaustively and is receiving further consideration, the results of which will be issued in due course.

The Association is indebted to the British Cotton Industry Research Association for valuable assistance.

The Director of the E.R.A. will welcome comments and criticisms from those who have occasion to use this specification.

I. FEATURES TO BE CONSIDERED IN THE EXAMINATION OF MATERIALS.

In order to produce a fabric of the highest quality a careful selection of the fibre is essential, and it should be treated at every stage with a view to the production of the best result. Consideration should therefore be given to the following :—

(*a*) The kind, class, source, grade and staple of the raw material employed (Clauses 1, 2, 3, 4, 40, 47 and 52).
(*b*) The count of yarn (Clauses 6, 29 and 55).
(*c*) Whether the yarn is single or folded, and, if the latter, the number of folds (Clauses 7 and 55).
(*d*) The number of spinning, or spinning and doubling, twists per inch of warp and weft respectively, and whether the twist is right-hand or left-hand (Clauses 30, 45 and 56).
(*e*) The strength of the yarn (Clauses 31, 55 and 56).
(*f*) The type of weave (Clauses 13, 14, 15, 16, 17, 46 and 57).
(*g*) The numbers of warp and weft threads (ends and picks) per inch (Clauses 18, 19, 20, 21 and 32).
(*h*) The weight of the fabric (Clauses 8 and 9).
(*j*) The thickness of the fabric (Clause 33).
(*k*) The amount of the sizing and filling materials and the mineral ash, and the effect of the sizing and filling materials on the electrical and mechanical properties of the fabric * (Clauses 10, 26, 34, 35, 36, 39 and 54).
(*l*) The extent to which the fabric has been scoured and/or bleached (Clauses 22 and 23).
(*m*) The effect of surface treatment, such as singeing, calendering, or beetling, on the fabric (Clause 24).
(*n*) The effect of chemical treatment, such as parchmentizing or mercerizing, on the yarn or fabric (Clause 25).

II. DEFINITIONS.

1. Kind.

The term "kind" refers to the actual fibre used, i.e. cotton, flax (linen) or silk.

* See Ref. L/S2, Tentative Directions for the Determination of the Electric Strength of Solid Dielectrics.

2. Class.

The term "class" refers to the variety of the specified fibre used, e.g. Sea Island Cotton.

3. Grade.

The term "grade" refers to the cleanliness of the fibre with respect to freedom from leaf and other impurities.

4. Staple.

The term "staple" denotes the average length of the bulk of the fibres being assessed.

5. Yarn.

The term "yarn" denotes the spun fibre.

6. Count.

The term "count" or "counts" applied to yarn denotes the relative fineness or coarseness of the yarn.

Note.—The use of the term "count" is sometimes applied to the number of threads per inch of the fabric, but this is incorrect.

(*a*) *Cotton Count.*

The term "cotton count" denotes the number of hanks, each consisting of 840 yards, contained in one pound (453·6 grammes) of yarn.

(*b*) *Linen Count.*

The term "linen count" denotes the number of leas (hanks), each consisting of 300 yards, contained in one pound (453·6 grammes) of yarn.

(*c*) *Raw Silk Count.*

The following systems are in general use :—

(i) *Raw Silk Ounce Count.*

The term "raw silk ounce count" denotes the number of lengths (hanks), each consisting of 1 000 yards, contained in one ounce (28·35 grammes) of raw silk.

(ii) *Raw Silk Dram Count.*

The term "raw silk dram count" denotes the number of drams per 1 000 yards of raw silk (1 dram $= \frac{1}{16}$ ounce $= 1\cdot772$ grammes).

(iii) *Raw Silk Denier Count.*

The term "raw silk denier count" denotes the number of deniers per 4 000 ells (= 520·57 yards) of raw silk.

1 denier = 0·825 grain = 0·0531 gramme.
Deniers per ounce = 533·3.
$\therefore$ 533·3 × 16 × 520·57 = 4 442 000 yards per lb. = denier silk.

(*d*) *Spun Silk Count.*

The term "spun silk count" denotes the number of hanks, each consisting of 840 yards, contained in one pound (453·6 grammes) of yarn (i.e. same as cotton).

(*e*) *Momme Silk.*

The term "momme silk" denotes fine silk fabric. It is generally sold by the weight per square yard, which is expressed in mommes.

NOTE.—The momme is a Japanese weight equivalent to 2·14 drams (1 dram = $\frac{1}{16}$ ounce = 1·772 grammes).

7. FOLDED OR DOUBLED YARN.

The term "folded" or "doubled" yarn denotes a yarn made of two or more threads twisted together.

NOTE.—If threads are composed of two-fold, three-fold, etc., yarns, they are described as 2/20s or 3/16s, etc., according to the count being 20s or 16s, etc.

In counting "doubled" spun silk there is a difference between the method adopted and that employed in the cotton trade, which may be illustrated as follows:—"2/60 cotton yarn" means two 60 count yarns twisted together resulting in a doubled yarn, which would only weigh 30 hanks to the pound (453·6 grammes). In the case of spun silk, however, 2/60 yarn would mean that two 120s count yarns had been doubled together to produce a doubled yarn weighing 60 hanks to the pound (453·6 grammes).

8. WEIGHT OF FABRIC.

The term "weight of fabric" denotes the weight of unit area of the fabric, and is expressed in ounces (avoirdupois) per square yard (grammes per square metre).

NOTE.—The weight in grammes of a piece of fabric 6·76 inches square is equal to the weight in ounces of a square yard.

9. WEIGHT OF TAPE AND WEBBING.

The term "weight of tape" (webbing) denotes the weight of unit length of tape (webbing) and is expressed in ounces (avoirdupois) per 144 yards.

10. SIZING.

The term "sizing" denotes the treatment of the yarn to hold the individual fibres together to enable it to withstand the frictional stress, and to smooth down the projecting fibres so as to reduce friction during weaving.

Size is also added to increase the weight of the yarn so as to produce a cheaper fabric.

In the cotton industry four kinds of sizing are in general use, as follows:—

(*a*) *Pure Sizing.*

The purpose of pure sizing is to enable yarn to weave. Although the sized yarn is increased by 5 per cent to 8 per cent in weight before scouring, very little, if any, additional weight is added to the resultant fabric. The materials used in the size mixtures are pure, and include sago, farina and occasionally flour, without any loading matter whatever. A little tallow or soap is usually put in for softening purposes.

(*b*) *Light Sizing.*

Light sizing is similar to pure sizing, but 6 to 20 per cent by weight is added to the warp yarn.

(*c*) *Medium Sizing.*

Medium sizing adds from 20 to 80 per cent by weight to the yarn. The object of this sizing is to give cheap cloths a good "feel."

(*d*) *Heavy Sizing.*

Heavy sizing adds over 80 per cent additional weight to yarn, and is in general only applied to heavily "filled" fabrics for West African and Eastern markets.

NOTE.—For electrical purposes, (*a*) and (*b*) above are the only sizing treatments permissible, and, in general, pure sizing only should be specified.

11. GASSING.

The term "gassing" denotes the operation by which projecting fibres are removed from the surface of the yarn before weaving.

12. FABRIC.

The term "fabric" denotes the woven yarn and includes cloth, tape and webbing.

13. PLAIN WEAVE.

The term "plain weave" denotes a weave in which both warp and weft threads are over one and under one throughout, and this gives equal bending of the threads.

14. MATT WEAVE.

The term "matt weave" denotes a weave in which one or both series of threads work two or more ends or picks together; such as 2 × 2, 3 × 3 or 4 × 4 ends and picks, and these are known as 2 × 2, 3 × 3 or 4 × 4 matts.

15. TWILL WEAVE.

The term "twill weave" denotes any weave that produces a diagonal line across the fabric. The simplest twill weave is the 2 × 1 or 1 × 2, in which one thread is lifted once and is down twice.

NOTE.—By the use of a twill weave a fabric can be made heavier and more compact than if a plain weave is employed. In most fabrics the warp is twisted harder than the weft.

In 2 × 1 the ends are in excess of the picks.
In 1 × 2 the picks are in excess of the ends.
In 2 × 2 very often the ends equal the picks, but with a heavier weft than warp.

16. SATIN WEAVE.

The term "satin weave" denotes a weave in which no two consecutive warp ends intersect with successive picks.

NOTE.—The satin weave gives a smooth, even face to the fabric and allows one set of threads to be completely covered, the face threads being much greater in number than the other series of threads.

17. DOUBLE TEXTURE.

The term "double texture" denotes a weave in which two plain or other fabrics are woven together at one weaving. The two fabrics, though quite distinct, may change places to form stripes, checks or figures.

18. WARP.

The term "warp" denotes the series of threads placed longitudinally in the loom over any desired width.

19. END.

The term "end" denotes the individual thread of warp yarn, e.g. 90 ends per inch means 90 threads of warp yarn per inch.

20. WEFT OR WOOF.

The term "weft" or "woof" denotes the series of threads passing transversely in the loom, and put into the fabric by means of the shuttle. Weft yarn is usually softer spun than warp yarn, and is frequently spun anti-clockwise.

21. PICK.

The term "pick" denotes the individual thread of weft yarn passing from selvedge to selvedge.

22. SCOURING.

The term "scouring" denotes the operation of washing the fabric after weaving to remove the sizing materials and the natural wax from the fibre.

NOTE.—In varnishing a fabric in the loom state, i.e. before being scoured, there is a possibility of chemical action between the cellulose or varnish and the material used in the size. Such action may materially affect the strength and durability of a fabric as well as the efficiency of the varnish. From the point of view of "proofing" fabrics, experience in textile chemistry has shown that the best results can only be obtained on fabrics that have been freed entirely from extraneous materials. On the other hand, scouring slightly reduces the tensile strength of fabrics.

23. BLEACHING.

The term "bleaching" denotes the series of operations through which a "grey" fabric (i.e. a fabric made from yarn that has not been bleached or dyed) passes to remove the natural colour of the fibre and to obtain a white fabric.

24. SURFACE TREATMENTS.

(*a*) *Singeing or Dressing.**

The term "singeing" or "dressing" denotes the operation by which projecting fibres are removed from the surface of a cloth by burning.

(*b*) *Shearing.*

The term "shearing" denotes the operation in which a cloth is passed over rotating razor blades and shorn.

* In America the term "dressing" is synonymous with "filling" and not with "singeing."

(*c*) *Calendering.*

The term "calendering" denotes the operation of finishing a cloth by passing it between heated rollers under pressure.

NOTE.—The arrangement of rollers varies according to the kind of finish required.

(*d*) *Beetling.*

The term "beetling" denotes a process of cloth finishing in which the finish is produced by winding a cloth upon rollers or cylinders, and subjecting it to a rapid succession of blows from wooden hammers.

NOTE.—The beetle finish may be imitated by means of a special calendering process.

(*e*) *Chesting.*

The term "chesting" denotes a process of cloth finishing in which the finish is produced by calendering a cloth between heavily weighted rollers, and winding the cloth during the process on to one of the calender bowls or rollers.

25. CHEMICAL TREATMENTS.

(*a*) *Parchmentizing.*

The term "parchmentizing" denotes an acid treatment of cotton yarn or fabric to increase the lustre.

(*b*) *Mercerizing.*

The term "mercerizing" denotes a caustic soda treatment of cotton yarn or fabric to increase the lustre.

26. FILLING * (also referred to as Stiffening).

The term "filling" denotes the filling up of the inter stices of the fabric with some chemical compound to produce a smooth surface.

27. REGAIN.

(*a*) When referring to weave, the term "regain" denotes the difference between the length of a fabric and that of a thread when removed from the fabric.

(*b*) When referring to moisture, the term "regain" denotes the percentage to be added to the dry weight of a material in order to obtain the weight of that material under normal humidity conditions.

III. METHODS OF INVESTIGATION.

NOTE.—The rules of the Liverpool Chamber of Commerce provide for the investigation of the features of raw cotton, and the rules of the Manchester Chamber of Commerce provide for the investigation of the features of yarn and fabric.

28. CONDITIONING OF SPECIMENS FOR TEST.

Before the tests specified in Clauses 29, 30, 31, 32, 33, 34, 35, 36 and 37 are carried out, samples of yarn or single sheets of fabric shall be conditioned in a controlled atmosphere for not less than 18 hours. The controlled atmosphere shall have a relative humidity of 75 per cent and a temperature of from 15° C. to 25° C.

* In America the term "dressing" is synonymous with "filling" and not with "singeing."

The yarn or fabric shall be tested as soon as possible after removal from the controlled atmosphere, and in any case before three minutes have elapsed.

The specified relative humidity may be obtained by the use of a solution of calcium chloride in water, specific gravity 1·22 at 20° C. (32 grammes of calcium chloride in 100 grammes of solution). Sulphuric acid shall not be used.

To ensure that the relative humidity of the controlled atmosphere is maintained at the correct value it is necessary either that the temperature be kept very constant or the air must be circulated within the chamber. The surface of the calcium chloride solution should be large per unit volume of air space, as if it is not the rate of attainment of equilibrium is very slow.

The following apparatus has been found satisfactory in maintaining the relative humidity of the controlled atmosphere constant:—

The chamber consists of a cubical box, with sides 24 inches long, the floor of which is nearly covered by a dish containing the solution of calcium chloride of the correct density. The samples of yarn or fabric to be conditioned are placed on a shelf half-way up the box. Air is circulated, by means of a small fan, over the solution up through holes cut at two corners of the shelf, over the samples and down through holes at the opposite corners of the shelf.

The humidity of the air, which may be measured by wet and dry bulb thermometers if the velocity of the air past them is greater than three metres per second, attains a constant value about three minutes after the box has been closed and the fan started, unless the prevailing conditions are extreme. If a humidity near saturation or dryness is required it is necessary that the walls of the box should be non-absorbent.

A solution of calcium chloride in water is satisfactory when a relative humidity above 45 per cent is required, and this solution should be employed in preference to sulphuric acid of which the vapour is liable to be absorbed by the fabric.

The correctness of the strength of the solution should be checked from time to time by humidity readings. As an alternative to wet and dry bulb thermometers, which require a known air velocity, a dew-point thimble may be inserted in the box and used when the fan is not working; with either method a window is necessary to avoid opening the box.

The value of the relative humidity of the air due to the calcium chloride solution given above will not vary 2 per cent over a temperature range of 30 deg. C.

NOTE.—The method of conditioning given above cannot be applied to fabric in rolls, which must be cut up before conditioning.

29. Determination of the Count of Yarn.

The yarn shall be conditioned as specified in Clause 28 before the count is determined.

In order to determine the count of the yarn used in the fabric it is necessary to remove the individual threads. A piece of fabric shall be cut out and sufficient threads of each kind (warp and weft) shall be placed on the scale pan to balance the appropriate weight given below. The number of inches is the count. In the case of two-fold, three-fold yarns, etc., the threads must be separated.

(*a*) *Cotton and Spun Silk.*

In the case of cotton and spun silk, if N is the count the relation may be written thus :—

$$N \times 840 \text{ yards weigh 1 pound } (= 7\,000 \text{ grains} = 453\cdot6 \text{ grammes})$$

$$\therefore N \text{ inches weigh } \frac{7\,000}{840 \times 36} \text{ grains} = 0\cdot231 \text{ grain} = 0\cdot015 \text{ gramme}$$

In other words, the number of inches of a cotton or spun silk yarn which weighs 0·231 grain or 0·015 gramme is the count of that yarn.

(*b*) *Linen.*

In the case of linen, if N is the count the relation may be written thus :—

$$N \times 300 \text{ yards weigh 1 pound } (= 7\,000 \text{ grains} = 453\cdot6 \text{ grammes})$$

$$\therefore N \text{ inches weigh } \frac{7\,000}{300 \times 36} \text{ grains} = 0\cdot646 \text{ grain} = 0\cdot042 \text{ gramme}$$

(*c*) *Raw Silk.*

In the case of raw silk the appropriate values given in Clause 6 shall be adopted.

30. Determination of the Twist of Yarn.

The yarn shall be conditioned as specified in Clause 28 before the twist is determined.

A suitable method for the determination of the twist of yarn is described in " Technical Testing of Yarn and Textile Fabrics," by J. Herzfeld, as follows :—

The apparatus consists of a base plate on which is fixed a frame supporting two small shafts (see Fig. 1).

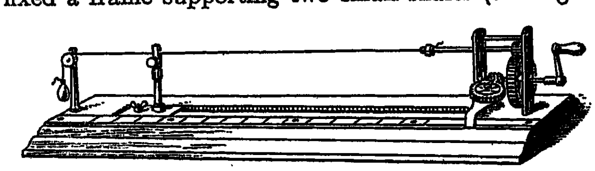


FIG. 1.—Apparatus for the Determination of the Twist of Yarn.

The lower shaft is fitted with a crank, and carries a spur wheel which engages with a pinion on the upper shaft, the gear ratio being 10 to 1. The lower shaft also rotates the graduated plate of a counter by means of worm gearing. The free end of the upper shaft terminates in a catch for holding one end of the yarn under test, which passes through a small split catch and then over a pulley as shown in Fig. 1. The support with the split catch is movable over a distance of 15 inches along a groove in the base plate, and can be fixed in any desired position by means of a thumb-screw, the position being indicated by a graduated scale on the plate.

To determine the twist of a yarn, the zero on the counter is adjusted to coincide with a fixed pointer. The movable support is placed in the position corresponding to the length of the sample of yarn it is desired to test, and one end of the latter is fastened in the catch fixed at the end of the upper shaft. The yarn is passed through the split catch on the top of the movable support, and then over the pulley, the free end being fastened to a small weight, the value of which varies according to the strength of the yarn, being heavier for stout and lighter for weak yarns. The split catch on the movable support is then screwed up, the lower shaft rotated by the crank and the yarn untwisted, the number of twists being recorded by the counter and read off direct. The counter will register either right-handed or left-handed twists.

Other suitable methods for the determination of the twist of yarn are described in the *Journal of the Textile Institute*, March 1922, page 81.

31. Tensile Strength of Yarn.

The yarn shall be conditioned as specified in Clause 28 before the test for tensile strength is carried out.

The tensile strength of yarn shall be determined by means of a single thread tester. A suitable apparatus for carrying out this test (Goodbrand) is described in the *Journal of the Textile Institute*, July 1923, as follows :—

> "The Goodbrand tester is one of the constant traverse pendulum-balance type, the load being applied by a falling weight, the motion of which is regulated by a plunger in an oil dashpot. The load is registered by the motion of a pendulum over a graduated arc, the pendulum being prevented from falling back when the specimen breaks by means of a small ratchet."

Another suitable method for the determination of the strength of yarn is described in "Technical Testing of Yarn and Textile Fabrics," by J. Herzfeld.

Ten breaking tests shall be carried out, and the maximum, minimum, and mean valves of the tensile strength of the yarn shall be stated.

32. Determination of the Number of Warp and Weft Threads per Inch.

The fabric shall be conditioned as specified in Clause 28 before the determination of the number of warp and weft threads per inch.

In the determination of the number of threads per inch it is not satisfactory to count the threads over a fraction of an inch and then multiply by a factor.

The number of threads shall be counted over a complete inch by means of a microscope cloth counting glass.

Note.—A suitable form of instrument for this purpose is supplied by Messrs. J. Casartelli & Son, Manchester.

33. Determination of Thickness of Fabric.

The fabric shall be conditioned as specified in Clause 28 before the thickness is determined.

The thickness of the fabric shall be measured by means of a ratchet micrometer* fitted with an anvil not less than ⅜ inch and not more than ½ inch diameter.

The average thickness of the fabric shall be ascertained as follows :—

A test piece one foot long and the full width of the roll shall be taken sufficiently far from the end to be representative of the bulk of the fabric. Ten measurements of thickness equally spaced diagonally across the test piece shall be made.

The maximum, minimum and mean values of the thickness shall be stated.

34. Tensile Strength of Fabric.

The fabric shall be conditioned as specified in Clause 28 before the test for tensile strength is carried out.

Nine specimens shall be cut in such a manner as to be representative of the bulk of the fabric. Three specimens shall be cut in the direction of the warp, three in the direction of the weft and three on the bias at an angle of 45°. No two specimens cut in the same direction shall contain the same longitudinal threads.

The specimens shall be not less than 2¼ inches wide, and the threads frayed out from each side to reduce the width of 2 inches. The specimens shall be placed evenly in the jaws of the testing machine so that the unstretched length of the fabric between the jaws is not less than 7 inches. The load shall be applied at a uniform rate, and the time taken to reach the breaking load from the commencement of the application of the load shall be one minute. If the specimen breaks unevenly, or in or at the jaws, due to incorrect clamping, a duplicate test shall be made on another test piece including the same threads. The maximum, minimum and mean values of the three tests warp way, of the three tests weft way and of the three tests on the bias respectively shall be stated.

Tests shall be carried out at the following temperatures :—

20° C., 60° C., 90° C. and 120° C.

Note.—When testing at the high temperatures the specimen should be surrounded by a heated cylinder to maintain the required temperature.

35. Tearing Strength of Fabric.

The fabric shall be conditioned as specified in Clause 28 before the test for tearing strength is carried out.

The tearing strength test shall be carried out by means of the apparatus shown in Fig. 2 as follows :—

The resistance to tearing shall be proved by the load required to tear a tongue 2 inches wide, commencing from holes $\frac{1}{32}$ inch diameter punched out of the fabric.

The size of each separate specimen tested shall be 12 inches by 6 inches.

(*a*) Three tests shall be made with the tear in the direction of the warp of the fabric.

(*b*) Three tests shall be made with the tear in the direction of the weft of the fabric.

* The permissible limits of the torque of the ratchet stop are under consideration.

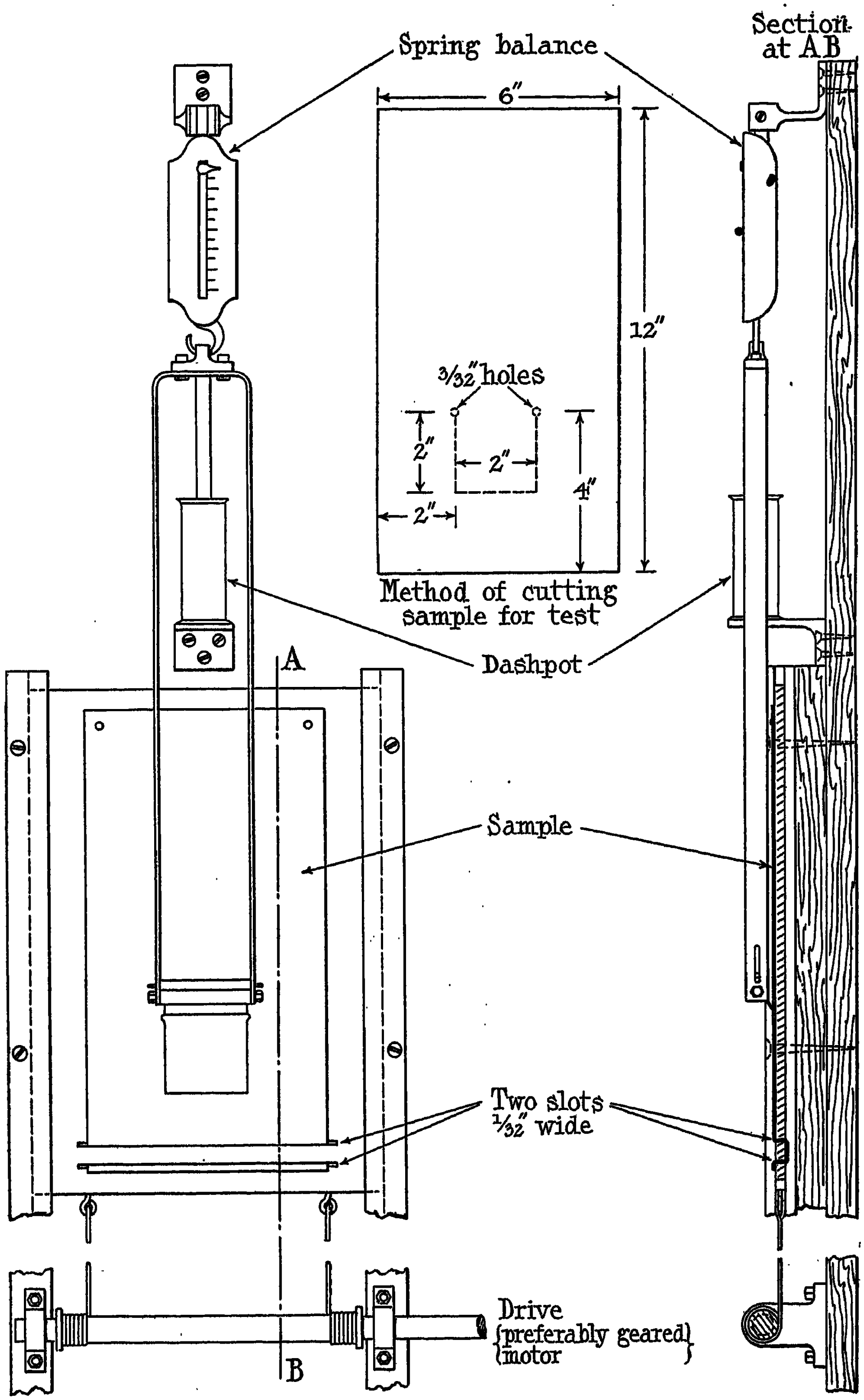


Fig. 2.—Apparatus for measuring the Tearing Strength of Fabric.

The method of carrying out the tearing test shall be as follows :—

Prepare the fabric specimen as shown in Fig. 2. Attach the lower end of the specimen to the sliding board by passing the fabric through the slots and pulling it tight. Grip the tongue of the fabric already cut out, as indicated by the dotted line, by passing it round and between the rollers which are attached to the spring balance. Pin the upper portion of the fabric to the board by two pins as shown in Fig. 2.

Rotate the winding gear so that the fabric tears at the rate of approximately 12 inches per minute. (A motor drive is recommended.)

Watch the balance and average the slightly varying values of the pull observed.

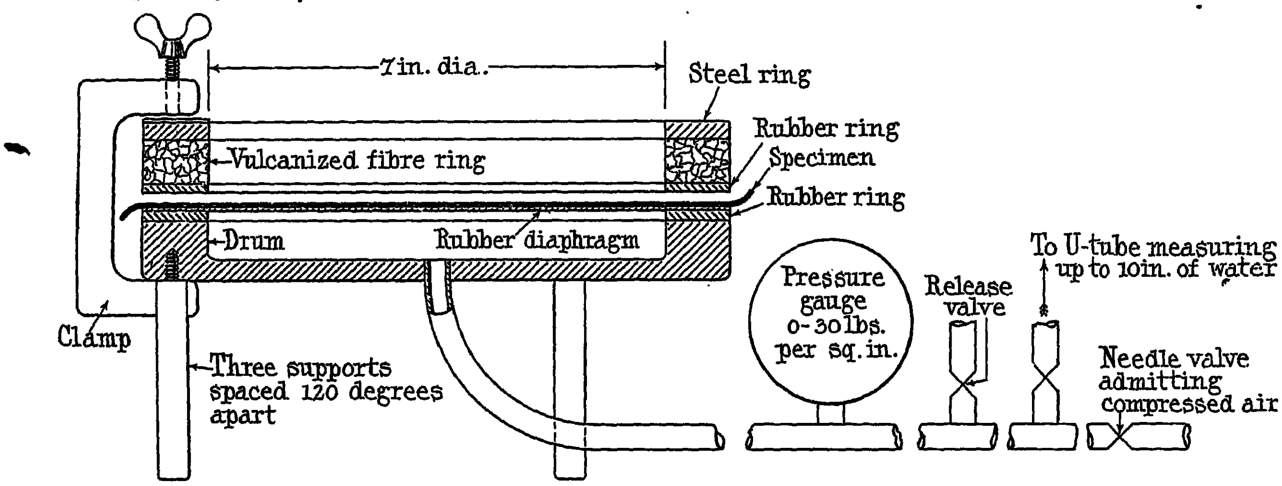
The maximum, minimum and mean values of the tearing strength in the directions of the warp and weft respectively shall be stated.

a rate that the radii of curvature of the fabric can be determined by means of a suitable spherometer. Sufficient readings shall be taken to enable a curve to be plotted showing the relationship between the air pressure and the radius of curvature of the fabric.

37. Ageing.

The tendency of the fabric to deteriorate with age shall be determined by the change in the bursting strength after it has been heated at a temperature from 90° C. to 95° C. for four weeks.

Bursting strength tests shall be carried out as specified in Clause 36 as soon as the temperature of the specimen has fallen to 20° C. (± 5° C.), and also after the fabric has been subjected to the controlled atmosphere specified in Clause 28 for not less than 18 hours.



NOTE:—The rubber ring and diaphragm are shown apart, but when in use they are brought into contact with the specimen and fixed by clamps, one of which is shown in position.

Fig. 3.—Apparatus for measuring the Bursting Strength of Fabric.

36. Bursting Strength and Extensibility of Fabric.

The fabric shall be conditioned as specified in Clause 28 before the tests for bursting strength and extensibility are carried out.

The bursting strength tests shall be carried out by means of the apparatus shown in Fig. 3 as follows :—

The fabric shall be placed over the rubber diaphragm and clamped between the rubber insertion rings fitted on top of the steel drum so as to make an airtight joint. Air shall be pumped into the drum at such a rate that the pressure on the fabric is increased gradually at the rate of approximately 30 lb. per square inch per minute until failure occurs.

Note.—Care must be taken to release the air pressure immediately the fabric fails so as not to damage the rubber diaphragm.

The test for extensibility shall be carried out on the apparatus shown in Fig. 3 as follows :—

The fabric shall be clamped between the rubber rings as before. Air shall be pumped into the drum at such

38. Tests for Acidity and Alkalinity.

(*a*) *Test with Distilled Water.*

A sample of fabric 6 inches square shall be boiled in a beaker for 5 minutes in 50 cm^3 of distilled water, the solution then being poured off into a flask, leaving the drained sample in the beaker. A further 50 cm^3 of distilled water shall be added to the sample and boiled for 5 minutes, the solution being poured off into the flask containing the first extract. To the contents of the flask (which need not be cooled) 0·5 cm^3 of 1 per cent phenolphthalein solution shall be added, and the whole titrated with N/100 caustic soda if acidity is indicated, or with N/100 sulphuric acid if alkalinity is indicated. The number of cm^3 of N/100 NaOH or of N/100 H_2SO_4 shall be stated.

A blank test shall be carried out on the water and glass vessels used in this test.

(*b*) *Test with Alcohol.*

A sample of fabric 6 inches square shall be boiled in industrial alcohol, complying with British Standard

Specification No. 2 D. 9, in the same manner as in (*a*). The procedure for the determination of acid or alkali specified in (*a*) shall be followed, and the number of cm^3 of N/100 NaOH or of N/100 H_2SO_4 shall be stated.

A blank test shall be carried out on the industrial alcohol and glass vessels used in this test.

NOTE.—The glass vessels used for these tests shall be boiled out several times with distilled water before the tests are carried out.

39. DETERMINATION OF THE AMOUNT OF SIZING AND FILLING MATERIALS AND MINERAL ASH.

(*a*) *Sizing and Filling Materials.*

Not less than one square yard of the fabric cut into small pieces shall be boiled for one hour in the liquids given below. A separate sample shall be used for each extraction.

(i) Distilled water.
(ii) 0·1 per cent solution of caustic soda, followed by an hour's boil with 0·5 per cent solution of hydrochloric acid.
(iii) Benzol complying with British Standard Specification No. 2 D. 10.

The extracts obtained shall be evaporated to dryness and the residues examined.

NOTE.—It is impossible to specify any simple procedure for the examination of the residues. The investigator must be guided largely by what he suspects to be present. (*See* Appendix I, Clause 54.)

(*b*) *Mineral Ash.*

Not less than 50 grammes of the fabric shall be dried at a temperature from 105° C. to 110° C. and then weighed with the usual precautions to obtain the dry weight of the sample. The fabric shall then be completely ignited, with all precautions against loss. The residue of incombustible matter (mineral ash) shall be weighed, and the amount computed as a percentage of the weight of the dried sample.

APPENDIX 1.

INFORMATION RESPECTING THE RAW MATERIALS AND PROCESSES EMPLOYED IN THE MANUFACTURE OF COTTON, LINEN AND SILK FABRICS.

40. CLASS AND SOURCE OF RAW COTTON.

Cotton is the seed hair from several species of the genus Gossypium—plants of the mallow family. The fibre is hollow and when growing is a single straight cylindrical cell, but on ripening the tube flattens and becomes contorted and twisted. The presence of these twists in the fibre makes it possible to spin it. Similar seed hair fibres to those found in the varieties of cotton used, but having no natural small twists in the fibre itself, are common, but cannot be spun economically. The number of twists in a mature cotton fibre varies from 150 to 400 per inch, the longer staple fibres having the highest number of twists per inch. The diameters of the fibres vary from 0·63 to 0·84 mil, the long staple Sea Island and Egyptian yarns having smallest diameters.

The actual number of plants from which commercial cotton is obtained is probably only seven, although "Index Kewensis" lists forty-two species and mentions eighty-eight others.

The seven species are :—

(1) *Gossypium arboreum* ..	Ceylon and Arabia.
(2) *Gossypium herbaceum* ..	Indian cottons.
(3) *Gossypium hirsutum* ..	U.S.A. Southern States cotton.
(4) *Gossypium barbadense* ..	Sea Island and West Egyptian and some Peruvian cottons.
(5) *Gossypium Peruvianum* ..	Native Peruvian cottons and Brazilian cottons.
(6) *Gossypium Sandwichense*	Sandwich Island cotton.
(7) *Gossypium tahitense* ..	Pacific Island cotton.

The classes of cotton commercially obtainable in Great Britain are given in the table on page 143.

From the point of view of textile manufacture Sea Island cotton produces the best yarn. It is the strongest and most uniform cotton and is used to spin the finest counts and the highest quality yarns. Specially good Egyptian cotton is suitable for yarns of 100 count and upwards, but good yarns of 60 up to 90 counts can be spun from ordinary good quality Egyptian cotton, and the cost of such yarns is less than that of similar counts spun from Sea Island cotton.

41. GINNING.

The term "ginning" is used to denote the process of separating the cotton fibre from bolls, seeds, immature fibre, etc. The process is imperfect, as portions of the seed and immature fibre pass on. It is carried out at the cotton plantations before the raw cotton is exported.

42. OPENING (BREAKING, BEATING).

The terms "opening," "breaking" and "beating" are applied to the processes through which the raw fibre passes in preparation for "carding," and consists of disintegrating, loosening and cleaning the matted fibre from the bales. The cotton after passing these processes is left in the form of a lap, i.e. in the form of a sheet 3 ft. 2 in. to 3 ft. 6 in. wide by ¼ in. thick which is rolled on an iron spindle for convenience in handling.

43. CARDING.

The term "carding" is applied to the process of opening up and combing the fibres and removing short and immature cotton and the dirt left in at the opening process. The cotton leaves the carding engine in the form of a sliver, i.e. a continuous length of loose, undeteriorated fibres.

NOTE.—In the production of fine grade counts, the carding process is frequently supplemented by a refined carding process known as combing.

44. Drawing.

The term "drawing" is applied to the process of drawing and placing straight and parallel the sliver produced in the carding engine in successive stages, until it is in suitable form for spinning. Only such twist as is necessary to keep the sliver intact is imparted during the drawing process. Drawing is effected in four or more stages on machines known respectively as :—

(a) Drawing frames.
(b) Slubbing frames.
(c) Intermediate frames.
(d) Roving frames.

The cotton leaves the roving frames on bobbins suitable for spinning.

45. Spinning.

The term "spinning" is applied to the process of twisting the cotton as it is received from the roving frames into a yarn. This twist produces a hard yarn which is incapable of further drawing.

Two methods of spinning are in use :—

(a) Ring spinning, which delivers the yarn on bobbins.
(b) Mule spinning, which delivers the yarn on cops.

46. Weaving.

In the operation of weaving, the warp threads are placed in the loom, and the thread that is to form the weft is wound into a "cop," which is placed inside the shuttle. The warp threads are led from the beam through the "healds" to the roller at the front of the loom to which they are fastened. When the loom is set in motion alternate threads, in the case of a plain weave, are pulled up and down respectively by the "healds" in such a way that the shuttle with its weft thread can be shot by the "picker" through the space between the upper and lower threads of the warp. A comb-like structure called the "reed" now pushes the weft thread, which the shuttle has left behind, up to the point where the warp threads separate. Then the "healds" reverse so that the thread of weft is gripped between the two layers of warp threads.

In weaving, the warp threads are subjected to considerable friction, which is liable to chafe the yarn and cause breakages. To prevent this damage the warp yarn is almost invariably sized before being woven.

47. Class and Source of Flax (Linen).

Linen is a vegetable fibre obtained from the flax plant *Linum usitatissimum.* The fibres themselves are constituted from small cells consisting of practically pure unlignified cellulose. Their average length is approximately 18 inches, but variations between 12 inches and 36 inches are commonly met. The mean diameter of the fibre is approximately 6 mils (varies between 1·8 and 25 mils). The fibre is separated from the woody tissue of the plant by a process of decomposition in stagnant water. Linen is a better conductor of heat than cotton, but contains approximately the same amount of hygroscopic moisture (approximately 8·5 per cent).

The following sources of flax are generally recognized :—

Russia : In 1913 over 90 per cent of the world's supply of flax was grown in the Russian Empire. Russian flaxes are known as Slanetz (dew-retted), Motchenetz (water-retted), and Siretz (ungraded fibre). The three kinds of flax are exported from Russia in no less than 32 varieties.

Holland : Dutch flax is exported in 6 grades.

Belgium : Flemish flax (blue flax) includes Bruges, Thisselt, Ghent, Lokeren and St. Nicholas, and is graded into 7 grades.

Courtrai flax is also graded into 7 grades.
Furnes and Bergues flax is graded A, B, C and D.
Walloon flax is graded II, III and IV.
Zealand flax is graded VI, VII, VIII and IX.
Friesland flax is graded into 10 grades.

France : French flax is known by districts in which it is grown, and includes Wavrin Fluies, Douai, Hazebrouck, Picardy and Harnes.

Ireland : Irish flax is known by the names of the counties in which it is grown.

Canada : Canadian flax is in no definite grades.

Austria-Hungary, Bulgaria, Italy, Netherlands also produce flax in smaller quantities.

(Attempts attended with a certain degree of success are being made to grow flax in Egypt, Bihar (India), Transvaal, Orange River Colony and various Australian districts.)

The flax passes through the following processes before it becomes the yarn used in the manufacture of linen tape and fabrics :—

48. Rippling.

The term "rippling" denotes a mechanical process of combing the flax seed capsules and other extraneous matter away from the actual stems (or "straw") of the plant itself.

49. Retting.

The term "retting" denotes the process of immersing the "straw" after rippling in stagnant water, so that by processes of decomposition and fermentation the pectoses and woody tissue of the plant are removed, leaving free the bast fibres.

50. Breaking.

Breaking is the term used to define the process of passing the retted fibre through rollers to break up the woody part of the stem in order that it may more easily be removed in the scrutching process.

51. Scrutching.

Scrutching is the term used to define the process of removing the woody parts of the stems to leave the fibres clean and free for subsequent spinning and weaving processes.

Linen yarn is available either "dry spun" or "wet spun." Wet spinning is employed to get higher counts

Class	Commercial name	Spins up to, counts	Quality	Colour	Staple length, inch
1	Sea Island	300	Regular and fine	Cream	$1\frac{3}{4}$
2	Meade	120	Regular and fine	Cream	$1\frac{3}{4}$
3	Egyptian :				
	Sakellaridis	150	Fine and soft	Ivory	$1\frac{1}{2}$
	Nubari	100	Fine, variable and rather harsher than above	Light brown	$1\frac{3}{8}$
	Abassi	100	Fine	White	$1\frac{3}{8}$
	Upper	60	Poorer and liable to be dirty	Dirty brown	$1\frac{1}{8}$
4	Sudan :				
	Sakellaridis	150	Fine and soft. Equal to good Egyptian Sakel	Light ivory	$1\frac{3}{8}$
	Zeidabi	60	Good grade, but liable to be dirty	White	$1\frac{1}{4}$
5	Brazilian :				
	Ceara, etc.	60	Hard and dirty	Dirty white	1
	Pernams, etc.	60	Hard and dirty	Dirty white	$1\frac{1}{8}$
6	Peruvian :				
	Sea Island	100	Soft and good grade	Varies	$1\frac{3}{8}$
	Mitafifi	100	Regular	Ivory	$1\frac{3}{8}$
	Tanguis	80	Good substitute for Egyptian and American extra staples	White	$1\frac{1}{4}$
	Smooth	60	Soft and good grade	White	$1\frac{1}{8}$
	Rough and mod. rough	—	Used chiefly for making shoddy, etc.	—	$1\frac{1}{4}$
7	American :				
	Orleans	60	Good grade, soft and strong	White	$1\frac{1}{8}$
	Uplands	50	Good grade and soft	White	1
	Texas	50	Good grade and soft	White	1
	Mobile	50	Moderate	White	$\frac{7}{8}$
8	East African :				
	American (Allen) ..	60	Substitute for American	White	$1\frac{1}{8}$
9	West African	—	This cotton is being developed, and is similar to American Uplands	—	—
10	Queensland :				
	American (Durango) ..	60	High grade, clean	White	$1\frac{1}{8}$
11	Indian :				
	Tinnevelly	20	Good grade, strong (can be spun in mixture with American)	Light brown	$\frac{7}{8}$
	Suntee Broach ..	20	Good grade, strong	White	$\frac{7}{8}$
	Madras Western ..	20	Moderate	Light brown	$\frac{3}{4}$
	Scinde	10	Inferior quality	Dirty white	$\frac{5}{8}$
	Bengal..	10	Hard and dirty	Light brown	$\frac{5}{8}$
12	Smyrna	20·5	The quality of this and other Turkish cottons is liable to vary on account of the tendency to grow native varieties	—	$\frac{7}{8}$
13	China	12	Although extensively grown and mostly used in China, in general is a good grade white cotton and short staple	—	$\frac{3}{4}$

(30 to 80), but dry-spun yarns are finer and are spun in counts 5 to 30.

52. Class and Source of Raw Silk.*

Silk is an animal fibre consisting of a continuous thread which is spun by the silkworm. This thread may be as long as 1 300 yards (2 000 yards for wild silks), and has a diameter varying from 0·5 mil to 1·0 mil (average 0·83 mil). The fibre is not cellular, but in its natural state consists of two continuous filaments, an inner substance known as fibroin and an outer substance known as sericin, cemented together. In silk in its manufactured state this cement is frequently partially removed (degumming).

Silk is an extremely hygroscopic material, and under favourable conditions may absorb 30 per cent of its weight of moisture and yet still appear dry. In its normal commercially "conditioned" state, silk contains 9·91 per cent moisture ("regain" 11 per cent), and is therefore some 40 per cent more hygroscopic than cotton.

The following table shows the chief varieties of silk :—

Bombyx mori	Japan
Bombyx mori	Italy
Bombyx mori	China
Bombyx fortunatus	Bengal
Bombyx textor	India
Antheræa mylitta	India
Attacus ricini	India
Attacus ricini	America
Attacus cynthia	India
Attacus silene	India
Attacus atlas	India
Antheræa yamamai	Japan
Cricula trifestrata	India
Antheræa peruyi	China

The filaments from the cocoon may be worked up and put on the market either as :—

(*a*) *Thrown Silk Yarn.*

Thrown silk yarn is made from silk filaments by running any number of them together and applying a slight twist.

(*b*) *Spun Silk Yarn.*

Short filaments of silk can only be made into yarn by the application of considerably more twist than that employed for thrown silk yarn. Spun silk is generally composed of filaments from 1 to 3 inches long, held together by a comparatively large number of twists per inch, in the same manner as a cotton thread. Spun silk is invariably made from filaments from which all the gum has been removed.

(*c*) *Schappe.*

Schappe is the name given to certain spun silk obtained from the Continent. It is usually of a slightly inferior quality to ordinary spun silk and is often made from silk waste containing from 5 to 10 per cent of gum.

* The E.R.A. is giving further consideration to the study of silk, the results of which will be issued in due course.

53. Raw Silk : International Titre.

The fineness of raw silk thread is expressed according to the International Standard as the number of deniers (0·0531 gramme) a skein of 500 metres length will weigh. This number is frequently referred to as the "international titre" and may be converted to the titres of other nations as follows :—

To Turin titre by multiplying by 0·8931.
To Milan titre by multiplying by 0·9315.
To French titre by multiplying by 0·8964.
To Italian (legal) and Swiss titres by multiplying by 0·9000.

54. Sizing Materials.

In the weaving process the warp threads are subjected to considerable stress and friction, which are liable to cause breakage and fraying of the fibres of which the yarn is composed. To prevent this damage to the warp thread it is almost invariably sized before being woven.

The materials used for sizing may be divided into three classes according to the purpose for which they are added.

(*a*) *Agglutinants.*

The function of an agglutinant is to hold together the individual fibres of the yarn, rendering them less liable to be frayed during the process of weaving and also to smooth and consolidate the yarn to enable it to withstand the stress and friction to which it is subjected whilst being woven. An agglutinant is used in addition to bind together the particles of clay or other mineral matter in the interstices of the yarn.

The materials used as agglutinants are as follows :—

Wheat flour.
Farina.
Corn starch.
Sago.
Rice flour.
Tapioca.
Dextrin.
Soluble starch.
Iceland and Irish moss.
Gum tragacanth.
Gum tragasol.

(*b*) *Softening Materials.*

The starch or gummy materials mentioned above, when applied in the pure state to the yarn, render it too stiff and harsh for satisfactory weaving, and it is necessary to add something that will give pliability and softness to the sized threads.

The softening materials generally employed are as follows :—

Tallow.	Japan wax.
Palm oil.	Spermaceti.
Castor oil.	Oleine oil.
Cotton-seed oil.	Soap.
Coco-nut oil.	Magnesium chloride.
Stearine.	Calcium chloride.
Paraffin wax (not for bleached fabrics).	Glycerine.
	Glucose.

(c) *Antiseptics.*

Flour, which is one of the most common ingredients of size, is a material well suited for the growth of mildew provided the conditions are favourable. To prevent the possibility of the formation of mildew it is necessary to make a further addition to the size, in the form of a "poison" which is termed an "antiseptic."

The antiseptic most frequently employed is :—

Zinc chloride.

Other antiseptics less frequently used are as follows :—

Zinc sulphate.	Salicylic acid.
Carbolic acid (phenol).	Thymol.
Cresylic acid.	Formaldehyde.

(d) *Remarks.*

It will be noted that the quality and quantity of the sizing materials used vary considerably. They differ in chemical composition in the properties that they impart to the yarn, and are as a rule more liable to undergo chemical change than cotton. The materials employed as softeners in sizing sometimes contain appreciable quantities of free acid and other impurities. Moreover, wax may prevent the varnish from adhering firmly to the fibres.

If size ingredients are left in a fabric, chemical action may develop which will be injurious to the cotton and the varnish. Thorough scouring therefore appears to be essential, and only such materials should be used in size as are harmless and can be removed readily from a fabric by scouring.

APPENDIX II.

MISCELLANEOUS.

55. SELECTION OF SUITABLE COTTON YARNS.

The selection of suitable counts of cotton yarns, the determination of whether the yarns shall be carded or combed, single or folded, and the number of spinning or spinning and doubling twists to be put into each inch of yarn are matters of great importance.

A count of yarn may be too high or too low for a given fabric, but the nature of the processes adopted to spin and double a yarn will in other respects determine its suitability.

The quality of a yarn is determined by the properties of the fibres of which it is composed and by the treatment they receive. For example, a carded yarn is inferior to a combed yarn in strength, uniformity of structure and homogeneity, even when both are made from the same class and grade of cotton. The number of spinning twists per inch of thread has a marked effect upon the strength of the thread, and doubling affects it still further.

Single commercial cotton yarns are much cheaper than folded yarns of equal count, and are spun from cotton of less value than that used for folded yarns. Two-fold commercial yarns are 25 per cent (or more) stronger than single yarns of equal count. When, however, single and folded yarns are spun from the same cotton the difference in strength will be less, as exceptionally good cotton is used for the single yarn, whilst normal quality cotton is employed for the two-fold yarn. Single and two-fold yarns of equal count differ in every respect, except that the same length of each has the same weight.

Good two-fold yarns are stronger, more durable, more uniform in strength and diameter than single yarns of equal count.

56. TWIST IN YARN.

Spinning twist binds together the short fibres composing a yarn and thus prevents them from slipping asunder when the yarn is subjected to tensile stress; it is a compression force that appears to act on the fibres in arithmetical retrogression. Thus, assuming a thread to have 12 twists to 1 inch, the sum of the numbers 1 to 12 is 78, and the compression which results from the first twist is 12/78 of the total compression; that of the second twist equals 11/78 and so on down to the twelfth, which equals 1/78. The number of spinning twists, however, and the strength of a yarn are not comparable, for each additional twist strengthens the yarn until a certain number per inch has been reached and then the strength decreases with each additional twist. Moreover, neither the increase nor the decrease in strength per twist is uniform. Twist has ceased to be beneficial when a shearing stress is produced, but this occurs after the maximum strength is attained. A yarn possessing the maximum strength is always hard, and has a tendency to kink and to snap when under tensile stress. Varnish cannot readily permeate a hard spun or twisted yarn, and in comparison with a normally twisted yarn of equal count there are larger interstices between the threads of a fabric.

A spinner generally puts the minimum number of twists into a yarn, as each additional twist reduces the output of a machine. Slight changes, however, have to be made from time to time as the spinning properties of one consignment of cotton differ from those of another. The twist is based upon the square root of the count number multiplied by a constant, but spinners of different cottons use different constants.

The strength of a yarn is also influenced slightly by the direction of the twist during spinning. In the textile industry the direction of twist is referred to as "twist way" and "weft way"; the former means that the fibres are twisted clockwise and the latter counter-clockwise.

57. SELECTION OF A SUITABLE WEAVE.

The type of the weave influences the number of warp and weft threads that may be used with advantage in each inch of fabric, and upon the number selected the value of the resulting fabric will depend to a large extent. With a plain weave it is impossible to use as many threads per inch as with such weaves as matt, twill, satin and double texture, but a plain weave holds every thread in position more securely than those mentioned above. It is on this account that plain woven fabrics tear so readily, as when a tearing stress

is applied the threads break one by one in regular succession. In less firmly united fabrics the threads slide against each other when under stress, and this prevents them from being broken singly. The bursting strength of a plain woven fabric is also less than that of any of the weaves mentioned above.

58. Information regarding Regain.

(*a*) When referring to weave, the term "regain" denotes the difference between the length of a fabric and that of a thread when removed from the fabric. Regain is, in general, an indication of good or bad weaving,* for, if it is different in the warp and the weft of a scoured plain woven fabric, the fabric will not stretch uniformly under tensile stress in both directions. If the regain in the warp exceeds greatly that in the weft it suggests that the tension upon the warp was insufficient during weaving. Should the regain in the weft exceed greatly that in the warp the inference is that the warp was excessively taut during weaving.

(*b*) When referring to moisture, the term "regain" denotes the percentage to be added to the dry weight of a material in order to obtain the weight of that material under normal humidity conditions.

The amount of regain is a more or less arbitrary percentage, and the values have been agreed upon in the textile industries, as follows :—

Material	Percentage regain
Cotton	$8\frac{1}{2}$
Linen	12
Silk	11

Note.—Many materials are naturally hygroscopic, i.e. possess the property of absorbing moisture from the atmosphere. The factors controlling the amount are various—the principal being temperature and humidity of atmosphere.

Under normal conditions there is an average moisture content which is peculiar to the material in question.

Textile fibres possess this property in varying degrees, depending to some extent on origin and manufacture.

In buying and selling, therefore, on a basis of weight, the moisture content becomes a very important factor.

There are official "conditioning houses" which determine the moisture content, and therefore the dry weight of the raw textile materials, by drying to constant weight at 105° C. to 110° C. To this dry weight is added a fixed percentage, which is assumed to be the percentage moisture content due to normal conditions of temperature and humidity. The new total weight is the "normal" weight for these conditions. The fixed percentage added is the "regain."

* This is a highly technical matter, and depends on the weight and build of the fabric.

A SURVEY OF AUTOMATIC ALTERNATING-CURRENT PROTECTIVE APPARATUS.

By B. NUTTALL, Student.

(ABSTRACT *of paper read before the* NORTH-WESTERN STUDENTS' SECTION, 19*th February*, 1924.)

ESSENTIAL CHARACTERISTICS FOR AN IDEAL PROTECTIVE SYSTEM.

(1) *Instantaneous isolation.*—Faults must be cleared quickly whilst only a small current is flowing, thus greatly reducing their destructive effects so that sound sections are not isolated and thus cause the supply to numerous consumers to be interrupted.

(2) *Property of discrimination.*—The apparatus should not operate on a heavy overload such as may be caused by a fault external to the area being protected.

(3) *Finality in adjustment.*—Once the protective gear is installed and adjusted on any feeder, there should be no readjustment of relays to suit any later modifications in any part of the network.

(4) *Simplicity of apparatus.*—The number of transformers and other component parts should be kept down to an absolute minimum as, generally speaking, the simpler the apparatus the more reliable it is in operation. The installation of a protective device must not incorporate any component part which is more liable to get out of order than the apparatus which it is desired to protect.

(5) *Adaptability to existing gear.*—With this should be associated flexibility for future extensions.

PROTECTION OF INDEPENDENT FEEDERS.

The removal of a fault on this type of feeder is necessarily accompanied by a temporary shut-down of the plant fed by the defective feeder. The object of protective gear for this type of feeder should be to confine the trouble to the part in question, and reduce to the smallest possible amount the duration of the dangerous condition. The following devices in more or less varied forms are employed for this purpose.

Plain overload devices.—The tendency except on very small systems (where fuses are installed) is to employ automatic circuit breakers in order to rupture the circuit safely with a minimum amount of disturbance, and thus save delay and expense in restoring the circuit. The drawback in most cases with plain overload trips is that transitory surges or momentary overloads necessitate settings which must be high enough to prevent the automatic features of the breakers from functioning and thus causing undesirable interruptions to supply. This procedure will result in the dangerous conditions—which it is desired to avoid—being permitted on the system, and these may be serious enough to cause extensive damage to the plant.

Time-limit overload devices.—To overcome this difficulty a device having an inverse time limit is usually employed. Two distinct types of time elements are available; one in the form of fuses and the other embodying some kind of air or oil dashpot device, or a piece of clockwork or equivalent mechanical device.

Leakage devices.—The modern tendency is to disconnect circuits when the insulation becomes so defective as to permit small leakages of current, for if these leaks are allowed to remain on the system and develop, there is a risk of fire and shock to the system, due to open sparking at the point. Overload devices will not protect against this condition, although if the leak occurs between phases it will probably develop into a short-circuit and thus cause the overload device to operate. All three-phase systems have their mid-point earthed through condensers connected in star fashion through the capacity of the cable. If there be no earth fault on any particular feeder or on the network connected thereto, the sum

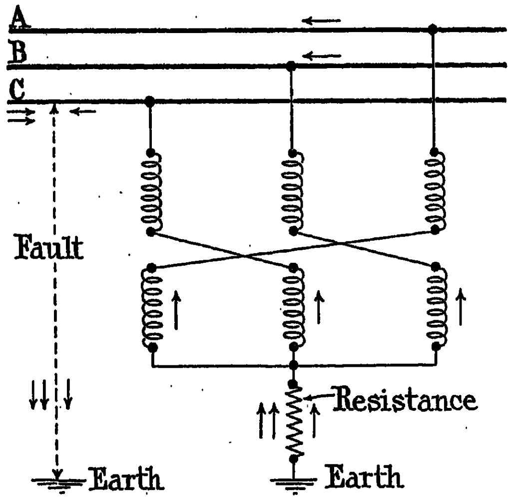


FIG. 1.—Zigzag method of earthing an insulated system by means of a static balancer.

total of the currents in the three cores must be zero at any instant.

Assume that a fault to earth develops on one phase, thus bringing this point of the system to earth potential. The capacity current from the other two phases must find its return path through the third phase lead, but as this lead is at earth potential the current cannot be passing via the dielectric and therefore the whole of the capacity current must pass from earth to the third phase via the fault.

A ring-type transformer of special design can be designed to operate a relay with 20 amperes fault primary current (or even less), and this relay may in turn close the trip circuit of the circuit breaker. We should thus have a protective arrangement capable of

being applied to any extensive distribution with unearthed neutral, whereby any cable would be automatically disconnected should a core develop a fault to earth, and this without any excessive rush of current with consequent shock to the system. The same result would be obtained in a system of much smaller capacity by connecting the neutral point to earth through a relatively high resistance, capable of passing, say, only 20 amperes if a pole became earthed. From the above it will be seen that it is advisable to earth the star connection of the system or, if this is not available, to earth the system through a transformer connected across the phase bars in zigzag fashion, one arrangement of accomplishing this being shown in Fig. 1.

Leakage devices operating on the principle outlined above are of two types; one in which the magnetic balance of the cores is utilized, and the other the current-balance method.

Protection of Interconnectors, Ring Mains and the Component Pieces of Apparatus of Generation, Transmission and Distribution Systems.

Under normal conditions the flow of power in an interconnector or ring main may be in either direction according to the load taken by the substations or large consumers "teed" off or connected directly to the system. It follows, therefore, that reversal is not a sign of leakage. This does not infer that reverse relays cannot be employed but is mentioned to point out that the use of reverse-power relays, even with a selective timing action, is restricted to comparatively simple arrangements. The use of reverse-power relays has a fairly wide range of application on existing systems, where little expenditure or little modification to switchgear is required, or where there is little or no synchronous machinery to fall out of step due, in certain cases, to the large time-lag on the relays.

The Merz-Price systems of protection.—There are two distinct types of protection under this heading, the circulating-current system and the balanced-voltage system. In each case a facsimile of the primary circuit condition at each end of the apparatus to be protected is reproduced in the secondary connections through the medium of current transformers, and these conditions are compared through the interconnection of the transformers by means of a pilot cable to determine whether the circuit conditions are normal.

Fig. 2 illustrates diagrammatically the circulating-current system, while the balanced-voltage system is shown in Fig. 3.

It will be observed that in both types a leak must occur within the protected zone for an unbalanced condition to be present in the secondary circuit. This unbalanced condition causes a current proportional to the leak to flow through the coil of the relay, and use is made of this facsimile of the primary leakage current, either directly or indirectly, to trip the breakers in the protected zone.

Compensated-pilot balanced-voltage Hunter-Beard system.—To eliminate the capacity effect of the pilot wires and thereby increase the stability and sensitiveness of the relays, the compensated-pilot system was invented. In this system each core of the pilot cable is surrounded by a sheath which is discontinuous at the centre, so that all the capacity current must flow

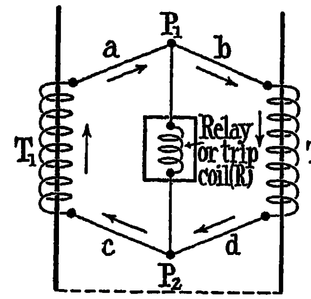


FIG. 2.—Diagrammatic representation of the Merz-Price circulating-current system of protection.

from the core to the sheath. The sheath is connected in such a way that the capacity current circulates in the circuit comprised by the pilot core, sheath and protective transformers. Consequently the capacity current is shunted from the relay coils, and the system becomes immune from any tendency to operate due to the passage of heavy short-circuit currents.

Merz-Hunter split-conductor protective system.—This system may be looked upon as a parallel-feeder system or duplicate ring-main system, having the advantages that for a given total current-carrying capacity, (1) it is more economical both from the point of view of initial cost of cable and switchgear and also from

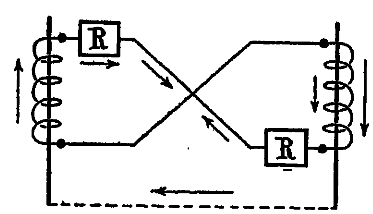


FIG. 3.—Diagrammatic representation of the Merz-Price balanced-voltage system of protection.

economy in operation, and (2) it is more sensitive to faults and more reliable in operation than separate cables protected by interlocked current-balance relays, Merz-Price balanced-voltage or other feeder systems which necessitate separate cables for each three-phase circuit. The system can also be applied to a limited extent to parallel feeders of similar capacity. The principle of operation is based on the fact that parallel conductors of equal impedance will share the current equally.

THE EFFECT OF OXIDATION ON THE HIGH-FREQUENCY RESISTANCE OF AERIAL WIRES: WITH A NOTE ON MEASURING THE RESISTANCE OF THICK WIRES.*

By L. B. TURNER, M.A., Member.

(*Paper received 26th September, 1924.*)

SUMMARY.

Measurements are made on thick solid and stranded wires to ascertain the effect on their high-frequency resistance of the oxide film formed by weathering. It is found that the weathering produces no sensible effect, under either dry or wet conditions.

The several methods of measuring high-frequency resistance are compared in respect of their suitability for determining the resistance of stout straight conductors.

(1) INTRODUCTION.

Recently studied methods † of reducing earth losses occurring near the aerial in high-power wireless transmitters have so much reduced the total resistance of the aerial circuit that the heat losses within the copper aerial and earth wires themselves assume considerable importance. Each of the wires, being substantially straight and remote from its neighbours, possesses a high-frequency resistance exceeding the direct-current resistance sensibly only on account of the "skin effect"; and this in straight, solid, circular, isolated conductors is calculable from well-known theoretical formulæ.‡ The wires of an aerial or earth system are, however, often stranded, so upsetting the circular distribution of current density on which the skin-effect calculations are based; and they are, moreover, usually coated with a more or less insulating covering of oxide or sulphide.

Theory indicates that with the solid wire the effect of such oxide film must be a rise in the high-frequency resistance, and it did not seem certain that there might not be—perhaps at the oxide-metal surface or in rain—a poorly conducting layer in which considerable losses would occur. With the stranded conductor the film might cause either a rise or a fall in the high-frequency resistance, according to the completeness of the insulation between the strands.

An admirable series of measurements on thick wires of various forms has been made by Kennelly and Affel.§ Their results with solid, round wires agree closely with theory; but although they investigated stranding they do not appear to have examined the effect of oxidation.

For these reasons the present measurements were made * on new bright and old black samples of solid and stranded wire, at wave-lengths ranging from 4 000 to 20 000 m. The familiar method was employed in which the resistance of the specimen is determined as the differences between the resistances of an oscillatory circuit when the specimen is included and when it is excluded.

In view of the suspicion with which high-frequency measurements of this sort must always be regarded by the critic † —and more especially when, as here, the conductor whose resistance is to be determined necessarily occupies a large space—the first series of resistance determinations was made in two quite different ways: (i) by the inserted resistance method (Lindemann), in which the unknown resistance is obtained in terms of a known resistance; and (ii) by the distuning method (Bjerknes), in which the unknown resistance is obtained in terms of known capacities and frequency.

(2) TESTS WITH SOLID HARD-DRAWN COPPER WIRE, 150 LB./MILE.

The test circuit employed is shown in Fig. 1. Here R_n and R_o are the specimens of wire, new and old ‡ respectively. Each was about 106 m long, wound in a zigzag form (a very flattened helix) over two parallel strips of wood as shown in Fig. 2. One or both of these specimens was short-circuited by the plug switches P_1 and P_2.

The main inductance coil L_1 consisted of 4 open spirals of copper tape, about 58 cm in diameter and of overall axial length 28 cm. The spirals were mounted on an axial wood rod, and were connected in series. The coupling coil L_2 (stranded wire, inductance 21μH, d.c. resistance 0·20 ohm) served to couple the test circuit very loosely to a triode oscillator set up at a distance.

The known resistance (r), insertable by removing the

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† For example, Alexanderson's multiple-earth antenna (*Proceedings of the Institute of Radio Engineers*, 1920, vol. 8, p. 263); Meissner's multiple earth connections (*Jahrbuch der drahtlosen Telegraphie*, 1921, vol. 18, p. 322) and T. L. Eckersley's earth screen (*Journal I.E.E.*, 1922, vol. 60, p. 581).

‡ It happens that aerial wires often lie between the useful ranges of the Rayleigh and Russell formulæ; but the comprehensive tables of Pedersen (*Jahrbuch der drahtlosen Telegraphie*, 1911, vol. 4, p. 505) or Circular No. 74 of the Bureau of Standards, p. 309, may conveniently be used.

§ "Skin-effect Resistance Measurements of Conductors at Radio Frequencies up to 100 000 Cycles per Second," *Proceedings of the Institute of Radio Engineers*, 1916, vol. 4, p. 523.

* At the Engineering Laboratory, Cambridge. The wire was supplied by the Post Office Engineering Dept., and the inductance coil in the test circuit was loaned from the Wireless Section, Engineer-in-Chief's Office, G.P.O., for the purpose of the tests.

† Every serious experimentalist with high-frequency currents knows that a good deal of experience, and after that a good deal of care, are required if quite gross errors are to be avoided. For an elaborate examination of the conditions for precision in this type of measurement, see S. LOEWE (*Jahrbuch der drahtlosen Telegraphie*, 1913, vol. 7, p. 365). With tedious precautions and corrections Loewe was able to reduce the final uncertainty to some 0·5 per cent. His difficulties, however, would have been somewhat reduced by the use of the modern triode generator.

‡ In use on a Post Office line for about 20 years.

plug P_3, was of fine eureka wire, and its value was either 1 or 2 ohms throughout the tests.

The condenser C was a mica plug box of high quality, supplemented by an adjustable air condenser showing a d.c. insulation resistance of over 100 megohms.

TABLE 1.

	ohms	μH
New specimen in circuit, old short-circuited	1·16	1 035
Old specimen in circuit, new short-circuited	1·18	1 038
New and old short-circuited ..	0·66	930
Hence :—New specimen ..	0·50	105
Old specimen ..	0·52	108

The measuring instrument M.V. was a Moullin voltmeter, calibrated by the makers between 0·4 and 1·5 volts at some acoustic frequency. The proportionality of the scale markings was checked at a wave-length of 4 km and found to be accurate.

In method (i), two tuned voltmeter readings V_1 and V_2 are obtained,* respectively without and with the known resistance (r) in circuit. The resistance R of the whole circuit (excluding r) is then given by $R = r/\{1 - (V_1/V_2)\}$. In method (ii), if C_1 and C_2 are the capacities at which the voltmeter reading is $1/\sqrt{2}$ of the tuned reading,† then

$$R = 1\,060\lambda(C_1 - C_2)/(C_1 + C_2)^2 \ddagger$$

where R is measured in ohms, λ in metres, and C_1 and C_2 in micromicrofarads. The resistance of the measurements made at the terminals of condenser C (set to zero) are set out in Table 1.

In order to exhibit the sort of agreement between resistance values measured by the two methods, they

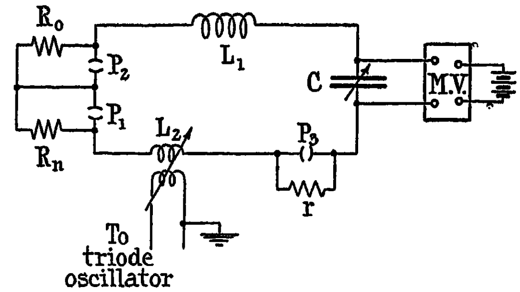

FIG. 1.

are set out side by side in Table 2, under "Circuit only" for the circuit of Fig. 1 with P_1 and P_2 plugged, under "Circuit + R_n" for plug P_1 out, and under "Circuit + R_o" for P_2 out.

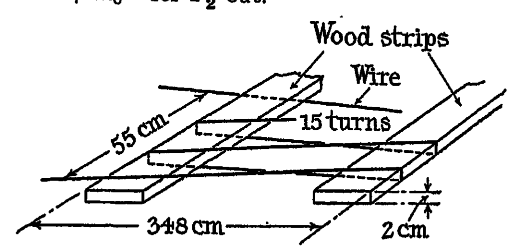

FIG. 2.

It will be seen that there is good agreement between the two independent methods; and it may be inferred that, even with an exceptionally awkward and wide-

TABLE 2.

*Measured Resistances, in Ohms.**

Wave-length	Circuit only		Circuit + R_n		Circuit + R_o	
	Method (i)	Method (ii)	Method (i)	Method (ii)	Method (i)	Method (ii)
km						
4	3·12	3·09	4·88	4·55	4·88	4·66
6	2·18	2·13	3·45	3·35	3·45	3·32
8	1·72	1·78	2·77	2·79	2·77	2·77
10	1·54	1·56	2·44	2·43	2·44	2·44
15	1·33	1·36	2·04	2·03	2·04	2·04
20	1·22	1·24	1·75	1·81	1·75	1·81

* That the 4th and 6th columns are exactly alike is accidental; it is not due to a mistake in transcribing the figures.

specimen, R_n or R_o, was found as the difference of the measured resistances of the whole oscillatory circuit when the specimen was included and when it was short-circuited. Two pairs of voltmeter or condenser readings were thus necessary for each determination.

The results of direct-current and low-frequency spread circuit such as obtains here, reliable measurements of high-frequency resistance can be made by either method.

The values of the high-frequency/direct-current resistance ratios taken from Table 2 [means from methods (i) and (ii)] are set out in Table 3. This table clearly shows that the presence or absence of a dry oxide film is quite without practical significance in solid

* V_1 was always made about 1·4 volt, and V_2 between 0·8 and 1·0 volt.
† Always made 1·40 volt.
‡ In lowly damped circuits as here.

TABLE 3.

High-frequency/Direct-current Resistance Ratios for Specimens of New and Old Solid Wire.

Wave-length	New wire	Old wire
km		
4	3·22	3·22
6	2·50	2·37
8	2·06	1·96
10	1·78	1·71
15	1·38	1·35
20	1·10	1·06

wires of such size and at such wave-lengths as here tested.

The effect of wetting was examined at wave-lengths of 4 and 20 km by thoroughly spraying the wires with rain water from a rose sprayer. In no case did the resistance of the specimen change by as much as 1 per cent.

(3) TESTS WITH STRANDED PHOSPHOR-BRONZE WIRE (7/19 S.W.G.).

This series of tests resembled that of section (1) almost precisely except that only the inserted resistance method [method (i)] was used, and that most of the space previously occupied by both solid specimens side by side was now occupied by either the new or the old stranded specimen. Measurements were therefore made at all wave-lengths on one specimen, which was then unwound and replaced by the other specimen.

The lengths of wire were each about 161 m; the d.c. resistances were 0·97 ohm (new) and 0·95 ohm (old). The observed high-frequency/direct-current resistance ratios are given in Table 4.

TABLE 4.

High-frequency/Direct-current Resistance Ratios for Specimens of New and Old Stranded Wire.

Wave-length	New wire	Old wire
km		
4	3·39	3·40
5	2·82	2·90
6	2·41	2·40
8	2·00	2·01
10	1·66	1·71
15	1·39	1·48
20	1·21	1·26

As in the case of the solid wire, wetting had no perceptible effect.

Again we find no important change of resistance due to oxidation, wet or dry.

As a further deduction from the results of these tests on aerial wires, it seems very improbable that appreciable gain is to be had by lacquering (or silver-plating) the large copper tubing used for inductance coils and connections in transmitting circuits.

(4) METHODS OF MEASURING RESISTANCE OF THICK WIRE.

The circuit method of resistance measurement, in either of the two forms here used, is so convenient, employing only simple apparatus found in any wireless laboratory, that it is worth inquiring whether the measurements described are capable of giving the true resistance of straight thick conductors such as may be used for aerials and earths. Two other methods have been employed for this purpose. Fleming* devised a balanced calorimetric method which appears to have given satisfactory results with very short lengths of rather thin conductors; and Kennelly and Affel † have published a full and excellent account of measurements of small resistances by a bridge circuit, in which the resistance of the specimen in one arm is balanced by

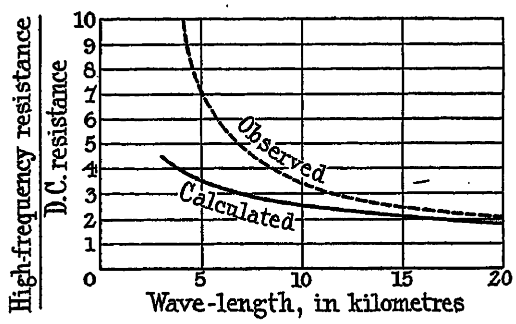

FIG. 3.—High-frequency/direct-current resistance ratio for solid copper wire, 300 lb./mile.

a known adjustable resistance in the other arm. Both these methods are more direct than the circuit method, but they require much more specialized apparatus which cannot be assembled from the everyday equipment of a laboratory.

Fig. 3 shows the calculated (i.e. true) high-frequency/direct-current resistance ratios for straight solid copper wire of 300 lb./mile (diam. 0·35 cm), together with values obtained experimentally precisely as in the case of the stranded wire in section (3). The divergence between the two curves shows that the form of the specimen and/or the circuit conditions were not such as to yield the resistance ratios actually sought.‡ In the following examination of the circuit method of measuring wire resistance, these tests on the 300 lb./mile wire form a convenient case for numerical reference.

Since the resistance (say a) of the specimen is obtained as the difference of the resistances of the oscillatory circuit with and without the specimen (say $A + a$ and A respectively), a must not be very much smaller than A. In the present instance A and a were about 2 ohms and 1 ohm respectively.§ In order to make a as large

* "Principles of Electric Wave Telegraphy and Telephony," 3rd edn., p. 144.

† *Loc. cit.*

‡ This does not vitiate the comparison between new and old wires in sections (2) and (3), since the new and old specimens were made rigorously similar.

§ At 10 km wave-length, $A = 1·80$ ohms, $a = 1·02$ ohms; d.c. resistance of specimen = 0·310 ohm.

as this, it was necessary to use as much as 161 m of the wire to form the specimen, which in consequence had very considerable stray capacities and an inductance of 214 μH (22 per cent of that of the rest of the circuit).

It would be difficult and costly to build up a circuit with much smaller resistance A using a coil of this inductance (L_1 of Fig. 1); and if the circuit were reproportioned with much smaller L_1 and correspondingly larger C, the change in the latter on retuning when the specimen is cut out would be so large as to necessitate an accurate knowledge of the condenser losses.

We are thus driven to use a large coil L_1 and a large length of wire in the specimen, and two factors making for error have therefore to be faced, viz.

(*a*) Effect of stray capacities, and
(*b*) Effect on each portion of the specimen of the neighbouring portions (proximity effect).

(*a*) *Effect of stray capacities.*—In the circuit of Fig. 4,

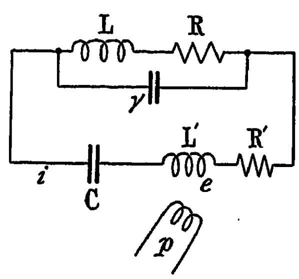

FIG. 4.

where γ may represent the self-capacity across a portion L, R of the circuit, it is easily shown that

$$e/i = R' + [1/(a^2 + b^2)][\{aR + bpL\} + j\{apL - bR + (a^2 + b^2)(pL' - 1/pC)\}]\ *$$

where $a = 1 - p^2L\gamma$, $b = pR\gamma$, and $j = \sqrt{(-1)}$. When the circuit is tuned for maximum i by adjustment of C or L', the imaginary term vanishes and the $LR\gamma$ impedance becomes a pure resistance, say ρ, where $\rho = (aR + bpL)/(a^2 + b^2)$.*

Substituting for a and b, and solving for R, we find

$$R = \frac{1 - \sqrt{\{1 - 4p^2\gamma^2\rho^2(1 - p^2L\gamma)^2\}}}{2p^2\gamma^2\rho}\ *$$
$$\fallingdotseq \rho(1 - p^2L\gamma)^2 *$$

when $4p^2\gamma^2\rho^2 << 1$, as in cases of stray capacity with $L\gamma$ far below resonance.

To frame a rough estimate of the self-capacity of the specimen, we may note that the static capacity between two parallel wires 161 m long, 0·175 cm radius, separated 3 cm, would be some 1 400 $\mu\mu$F; so that we may take (say) 500–1 000 $\mu\mu$F as the ideal concentrated capacity shunting our specimen, whose inductance is 214 μH. At 4 km ($p^2 = 2 \cdot 23 \times 10^{11}$), the measured value would in consequence exceed the true value of the resistance as shown in Table 5. Hence, although appreciable correction for self-capacity of the specimen is needed at the shorter waves, the error does not approach the discrepancy existing between the curves of Fig. 3.

* These expressions, which are exact, are useful in other connections, where the shunting capacity γ is not small.

The error caused by the stray capacity bridging the coil L_1 is likely to be smaller. The self-capacity of L_1 is not likely to exceed 200 $\mu\mu$F, and as the coil inductance is 95 μH the ratios here would not exceed $\rho/R = 1 \cdot 09$.

TABLE 5.

γ	ρ/R
500 $\mu\mu$F	1·05 times
1 000 $\mu\mu$F	1·10 times

Since the coil remains in circuit whether the specimen is in or out, its self-capacity causes error only in so far as it is altered by short-circuiting the specimen.

(*b*) *Proximity effect.*—It is possible to estimate this

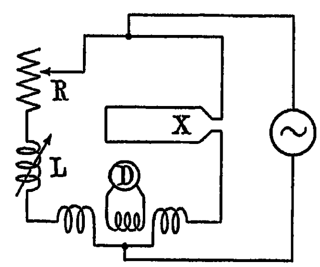

FIG. 5.

effect in our actual specimen only roughly, as the long pieces of thick wire, though nowhere allowed nearly to touch, spaced themselves unevenly except near the supports at the ends. Howe has shown* that an alternating magnetic field of frequency $p/(2\pi)$ and amplitude H C.G.S. electromagnetic units perpendicular to a round non-magnetic wire of radius r cm and resistivity ρ ohms per cm cube produces eddy-current heat at the rate of $(1/\rho)p^2H^2r^4 \times 3 \cdot 93 \times 10^{-17}$ watt per cm run. Remembering that H^2 is inversely proportional to the square of the space between wires, we may guess 1 or 2 cm as the equivalent uniform spacing in our specimen, and, doing so, may take the field cutting each wire as nearly that due to a single neighbouring wire. Using the above formula, we then find for the 161 m of copper wire, 0·175 cm in radius, at 4 km wave-length, a resistance additional to the straight-wire value of 6·1 or 1·5 ohms respectively. As the measured resistance at this wave-length was 3·2 ohms, it is clear that the proximity effect we are examining is competent to explain the discrepancy.

(5) THE MOST SUITABLE METHOD.

Although the circuit here used might with advantage have been modified in its dimensions—notably in spacing out the specimen more uniformly and widely—it is clear from the foregoing analysis that the circuit method is open to serious objections for the

* *Proceedings of the Royal Society*, A, 1916–17, vol. 93, p. 471.

measurement of the resistance of stout conductors; moreover, the difficulties discussed cannot be avoided by any variation of the manner in which the circuit resistance is measured, such as Pedersen's mercury-switch condenser-discharge method.* On the other hand, the calorimetric method is necessarily slow and troublesome; and, while it is capable of measuring quite short straight wires—75 cm in Fleming's apparatus—it requires the production and accurate measurement of large high-frequency currents. To develop heat in the specimen at the same rate as in Fleming's apparatus (about 1 watt per metre) a conductor no larger than our 300 lb./mile wire would require, at the wave-length of 20 km, a current as large as 18 amperes.

* *Wireless World and Radio Review*, 1922, vol. 10, p. 135.

Some bridge arrangement, such as used by Kennelly and Affel,* seems to be much the most suitable. Their circuit is shown in Fig. 5, copied from their paper, in which X is the specimen balanced by adjustment of L and R, and D is the detector. They used a generator current of some 5 amperes, and were able to measure low resistances such as 0·2 ohm with an uncertainty of only one-third of 1 per cent.

* *Loc. cit.*

INSTITUTION NOTES.

Members Practising as Consultants.

The attention of the Council was recently drawn to an advertisement of a Local Authority in which Chartered Electrical Engineers were invited to submit, in competition with each other, their terms for professional advisory work.

In the opinion of the Council such a proceeding is undesirable and not in the best interests of the Local Authority requiring advice.

The Council would consider it to be a breach of professional etiquette for a member of the Institution to reply to such an advertisement.

Where the names of a sufficient number of qualified consultants are not known to a Local Authority, the President of the Institution will always be willing to submit the names of qualified engineers for the purpose.

Associate Membership Examination Results: October, 1924.

Passed.

Amerasinghe, R. P. (London).
Bowden, G. H. (Hengoed).
Brakenridge, W. D. (Manchester).
Carter, J. W. (Birmingham).
Graham, E. E. (Durham).
Groves, T. J. (Derby).
Harris, T. E. (Blackheath, London).
Horowitz, H. (London).
Illingworth, T. (Norwich).
James, R. F. E. (Bilbao, Spain).
Jones, D. W. G. (New Ferry).
Kline, J. A. C. (London).
Lieberg, O. S. W. (London).
Morley, E. W. L. (Welling).
Murray, R. B. (Sale).
Newbery, A. F. (Birmingham).
Payne, N. B. (London).
Rayner, F. J. (Luton).
Redshaw, C. C. (Llanrug).
Sclar, I. (Cowdenbeath).
Steele, W. H. (Pontypridd).
Strickland, A. M. (Penrith).
Swale, W. E. (Stoke-on-Trent).
Welch, F. M. (Whitley Bay).
White, E. J. (Hartfield).
Williams, O. D. (Llanelly).
Wright, C. H. (Manchester).

Passed Part I only.

Bishop, J. L. (Southampton).

Passed Part II only.

Barron, W. (London).
Cater, C. (Harrow).
Cotsell, G. W. (Edinburgh).
Hall, M. H. (Sheffield).
Jackson, F. S. (Halifax).
Jones, L. K. (Newport, Mon.).
Paley, F. R. (Hove).
Wadham, G. A. (Shepperton-on-Thames).
Waring, A. J. (Torquay).

Officers of the Corps of Royal Engineers.

Passed.

de Lotbinière, 2nd Lieut. E. J.
Laurence, 2nd Lieut. K. St. G.
Rendell, 2nd Lieut. W. P.
Treays, Lieut. W. H.
Waring, 2nd Lieut. E.

Further results relating to candidates who sat for the Examination abroad will be published later.

Associate Membership Examination.

The next Examination will be held on the 2nd, 3rd and 4th April, 1925. Candidates must be either Students or Graduates of the Institution or have lodged with the Secretary a duly completed form "E" for election as Associate Member. Entry forms for the Examination, which must be completed and returned by the 1st February, may be obtained on application to the Secretary.

Supplementary Reserve of Officers.

The Council desire to draw the attention of members to the fact that it has been decided by the military authorities to form a Supplementary Reserve of Officers with a view to completing on mobilization the requirements of certain Arms and Branches of the Regular Army for which the existing Army Reserve does not provide. These requirements will be mainly technical, and officers commissioned into the Supplementary Reserve will be liable to serve, in the event of an emergency, with any unit or part of His Majesty's Land Forces in any part of the world, and they will be liable to be called out on service when the Army Reserve or any part of it is called out by proclamation. The liability to be called out in aid of the Civil Power will not, however, be enforced.

Officers will be divided into two categories, viz. those who are required to carry out training in peace

(Category B), and those who are not required to carry out any training owing to their duties after mobilization being similar to their peace-time professions (Category C). Personnel of both Categories are required for the Royal Engineers, and the Council hope that members of the Institution who are eligible will offer themselves for commissions in that Corps.

Candidates for commissions may be accepted from civil life, from the Regular Army Reserve of Officers, the Territorial Army, or the Territorial Army Reserve of Officers, and the maximum age limits are as follows :—

For appointment as

	Years
2nd lieutenant or lieutenant ..	30
Captain	35
Major	40
Lieutenant-colonel	45

Candidates must have qualified at an Army Entrance Examination or have passed the Matriculation Examination of a recognized university, or produce other evidence of their educational attainments. In addition, candidates will be required to furnish evidence of technical knowledge or qualifications fitting them for duty with the Corps.

Full particulars are given in Army Orders Nos. 284/1924, 285/1924, 286/1924, 287/1924, 299/1924 and 343/1924. Copies of these Orders can be obtained on application to the Secretary of the War Office, London, S.W., and applicants are requested to state that their attention has been drawn to the scheme by the Council of the Institution.

Representatives of the Institution on Other Bodies.

The following is a list of representatives of the Institution on other bodies, and the dates on which they were appointed.

Bradford Public Libraries Committee:
Mr. T. Roles (27 Feb., 1919).

Bristol University:
Mr. H. F. Proctor (6 Dec., 1917).

British Association, Fuel Economy Committee:
Mr. C. H. Wordingham, C.B.E. (9 Jan., 1919).

British Cast Iron Research Association:
Mr. E. B. Wedmore (25 Sept., 1924).

British Electrical and Allied Industries Research Association:
Mr. Ll. B. Atkinson (2 April, 1919).
Mr. F. Gill, O.B.E. (2 Nov., 1922).
Mr. R. T. Smith (30 Oct., 1919).
Mr. C. P. Sparks, C.B.E. (4 Oct., 1917).
Mr. C. H. Wordingham, C.B.E. (4 Oct., 1917).

Sectional Committee on Electric Control Apparatus Research:
Major H. C. Gunton (2 Feb., 1921).
Mr. C. H. Wordingham, C.B.E. (22 Nov., 1920).

British Electrical Development Association:
Mr. F. Gill, O.B.E. (13 Dec., 1923).
Mr. R. Hardie (18 Jan., 1923).
Mr. W. R. Rawlings (17 Jan., 1924).

British Engineering Standards Association:

Main Committee:
Mr. Ll. B. Atkinson (17 Jan., 1924).
Col. R. E. Crompton, C.B. (17 Jan., 1924).
Mr. C. H. Wordingham, C.B.E. (17 Jan., 1924).

Sectional Electrical Committee:
Mr. F. Gill, O.B.E. (21 May, 1914).
Mr. J. S. Highfield (21 May, 1914).
Mr. R. T. Smith (21 May, 1914).
Mr. W. B. Woodhouse (19 Dec., 1918).
Mr. C. H. Wordingham, C.B.E. (18 Nov., 1915).

Sectional Committee on British Standards in Colonial and Foreign Trade:
Mr. C. P. Sparks, C.B.E. (26 Oct., 1916).

Sectional Committee on Colliery Requisites:
Mr. C. T. Allan (3 July, 1924).

Sectional Committee on Illumination:
Prof. W. C. Clinton (28 Feb., 1924).
Lt.-Col. K. Edgcumbe (28 Feb., 1924).
Mr. P. Good (28 Feb., 1924).
Mr. H. T. Harrison (28 Feb., 1924).
Prof. J. T. MacGregor-Morris (28 Feb., 1924).

Sectional Committee on Machine Parts and their Gauging and Nomenclature:
Mr. J. H. Rider (8 Feb., 1917).

Sectional Committee on Petroleum Products:
Mr. H. W. Clothier (1 Feb., 1923).

Electrical Instruments Sub-Committee:
Lt.-Col. K. Edgcumbe (15 Feb., 1923).

Electrical Nomenclature and Symbols Sub-Committee:
Mr. C. C. Paterson, O.B.E. (8 Jan., 1920).

Overhead Transmission Lines Material Sub-Committee:
Mr. C. H. Wordingham, C.B.E. (30 Oct., 1919).

Pipe Flanges Sub-Committee:
Mr. W. M. Selvey (14 April, 1921).

Panel on Steel Conduits for Electric Wiring:
Mr. H. J. Cash (28 Sept., 1922).
Mr. F. T. Alldread (8 Dec., 1924).

Panel on Switches, Ceiling Roses and Wall-plug Sockets:
Mr. H. J. Cash (23 Jan., 1924).
Mr. F. W. Purse (23 Jan., 1924).

Sub-Panel on Graphical Symbols for Interior Installations:
Mr. J. R. Cowie (13 Nov., 1924).

Conference on Standardization of Ball and Roller Bearings:
Mr. W. M. Selvey (26 July, 1921).

Engineering Joint Council:
Mr. J. S. Highfield (28 Feb., 1924).
Mr. R. T. Smith (28 Feb., 1924).

Imperial College of Science and Technology, Governing Body:
Mr. W. M. Mordey (12 April, 1923).

Imperial Mineral Resources Bureau Conference:

Mr. J. H. Rider (23 Jan., 1919).
Mr. W. B. Woodhouse (23 Jan., 1919).

Copper Committee:

Mr. B. Welbourn (18 Sept., 1919).

Miscellaneous Minerals Committee:

Prof. E. Wilson (18 March, 1920).

Institute of Metals, Corrosion Research Committee:

Mr. W. M. Selvey (19 July, 1923).

Institution of Civil Engineers, Engine and Boiler Testing Committee:

Mr. R. A. Chattock (19 Oct., 1922).
Mr. C. P. Sparks, C.B.E. (19 Oct., 1922).

Institution of Heating and Ventilating Engineers, Committee on Utilization of Exhaust Steam and Waste Heat:

Mr. P. V. Hunter, C.B.E. (29 Sept., 1922).
Mr. W. M. Selvey (29 Sept., 1922).
Mr. J. C. Wigham (29 Sept., 1922).

International Illumination Commission, British National Illumination Committee:

Prof. W. C. Clinton (13 Dec., 1917).
Lt.-Col. K. Edgcumbe (27 Nov., 1913).
Mr. P. Good (18 Sept., 1919).
Mr. H. T. Harrison (27 Nov., 1913).
Prof. J. T. MacGregor-Morris (27 Nov., 1913).

International Testing Association:

Mr. Ll. B. Atkinson (29 May, 1919).
Mr. C. C. Paterson, O.B.E. (29 May, 1919).

Leeds Civic Society:

Mr. E. C. Wallis (27 March, 1919).

Leeds Municipal Technical Library Committee:

Mr. W. B. Woodhouse (19 Dec., 1918).

Loughborough Technical College, Advisory Committee:

Mr. R. B. Leach (27 March, 1919).

Metalliferous Mining (Cornwall) School Governing Body:

Mr. J. S. Highfield (18 Sept., 1919).

Middlesbrough Technical College, Governing Body:

Mr. J. M. Gibson (1 Oct., 1924).
Mr. A. M. Paton (1 Oct., 1924).

Mines Department, Electrical Storage Battery Locomotive Committee:

Mr. R. T. Smith (7 Dec., 1922).

National Physical Laboratory, General Board:

Mr. Ll. B. Atkinson (21 Oct., 1920).
Dr. A. Russell, F.R.S. (22 Nov., 1923).

Newcastle-upon-Tyne Chamber of Commerce:

Mr. A. P. Pyne (13 Nov., 1919).

Professional Classes Aid Council:

Mr. W. B. Esson (26 July, 1921).

Royal Engineer Board:

Mr. C. H. Wordingham, C.B.E. (7 April, 1921).

Royal Society:

Alloys of Iron Research Committee:

Mr. J. Swinburne, F.R.S. (15 Feb., 1923).

National Committee for Physics:

Dr. A. Russell, F.R.S. (16 Dec., 1920).

National Committee on Radio-Telegraphy:

Dr. W. H. Eccles, F.R.S. (4 Aug., 1920).
Dr. J. Erskine-Murray (3 July, 1934).

Scientific and Industrial Research Advisory Council, Engineering Committee:

Mr. J. S. Highfield (9 March, 1916).

Society of Radiographers:

Mr. S. W. Melsom (3 July, 1924).
Mr. C. C. Paterson, O.B.E. (22 Jan., 1920).
Dr. A. Russell, F.R.S. (25 May, 1922).
Mr. C. P. Sparks, C.B.E. (3 July, 1924).
Mr. A. A. C. Swinton, F.R.S. (22 Jan., 1920).
Mr. R. S. Whipple (23 Oct. 1924).

Transport Ministry, Advisory Panel and Committees:

Mr. Ll. B. Atkinson (30 Oct., 1919).
Sir J. Devonshire, K.B.E. (30 Oct., 1919).
Mr. J. S. Highfield (30 Oct., 1919).
Mr. R. T. Smith (30 Oct., 1919).
Sir John Snell (30 Oct., 1919).
Mr. C. P. Sparks, C.B.E. (30 Oct., 1919).
Mr. C. H. Wordingham, C.B.E. (30 Oct., 1919).

Union of Lancashire and Cheshire Institutes (Panel for Engineering).

Mr. A. P. M. Fleming, C.B.E. (28 Feb., 1924).
Prof. Miles Walker, D.Sc. (28 Feb., 1924).

Women's Engineering Society:

Mr. A. P. M. Fleming, C.B.E. (19 July, 1923).

The Benevolent Fund.

The following is a list of the Donations received during the period 26 November–24 December, 1924.

	£	s.	d.
"Anonymous" (Coventry)	5	5	0
Benger, W. A. (Otley)		5	0
Broadbent, D. R. (London)	2	2	0
Clay, C. B. (Bromley)	1	1	0
Downing, H. E. (Birmingham)		5	0
Hutton, F. W. (Frodsham)		5	0
Riley, F. (Blackburn)		5	0
Robinson, P. J. (Liverpool)		10	0

Accessions to Reference Library.

BAUR, C. Das elektrische Kabel. Eine Darstellung der Grundlagen für Fabrikation, Verlegung und Betrieb. 2e Aufl. 8vo. 409 pp. *Berlin*, 1910

BOARD OF EDUCATION. Report for the year 1923 on the Science Museum. 8vo. 20 pp. *London*, 1924

BOILEAU, C. Le chauffage électrique. Préface de [E.] Herriot. 8vo. 172 pp. *Paris*, 1920

BURNHAM, T. H. Special steels. A concise treatise on the constitution, manufacture, working, heat treatment, and applications of alloy steels. Chiefly founded on the researches regarding alloy steels of Sir R. Hadfield, Bt., and with a foreword by him. sm. 8vo. 216 pp. *London*, 1923

BUSQUET, R. Précis d'hydraulique : la houille blanche. sm. 8vo. 383 pp. *Paris*, 1905

CAPART, G. La protection des réseaux et des installations électriques contre les surtensions. Préface de L. Barbillon. 2e édition. 8vo. 231 pp. *Paris*, 1920

CERMAK, P. Die Röntgenstrahlen. 8vo. 130 pp. *Leipzig*, 1923

CHIROL, M. Appareils de mesures électriques. sm. 8vo. 332 pp. *Paris*, 1923

COTTON, H., *M.B.E.* Electrical technology. A textbook covering the syllabus of the B.Sc. Engineering, A.M.I.E.E., and the National Certificate examinations in this subject. 8vo. 391 pp. *London*, 1924

CROFT, T. Electrical machinery and control diagrams. 8vo. 317 pp. *New York*, 1924

CROTCH, A. The elements of automatic telephony. 8vo. 74 pp. *London*, 1924

DE BRUYNE, N. A. The electrolytic rectifier. Containing a chapter showing how to make and use a rectifier for charging accumulators from a.c. supply mains. sm. 8vo. 82 pp. *London*, 1924

DOWSETT, H. M. Wireless telephony and broadcasting. 2 vol. la. 8vo. *London*, 1924

DRYSDALE, C. V., *O.B.E.*, *D.Sc.*, and JOLLEY, A. C. Electrical measuring instruments. pt. 2, Induction instruments, supply meters & auxiliary apparatus. la. 8vo. 475 pp. *London*, 1924

EASON, A. B. Where to seek for scientific facts. sm. 8vo. 48 pp. *London* [1924]

ELECTRICITY COMMISSION. Fourth annual report of the Electricity Commissioners. 1st April, 1923, to 31st March, 1924. la. 8vo. 146 pp. *London*, 1924

—— Electricity (Supply) Acts, 1882–1922. London and home counties electricity district. Draft Order and Scheme under Section 7 of the Electricity (Supply) Act, 1919. 8vo. 52 pp. *London* [1924]

—— Generation of electricity in Great Britain. Year ending 31st March, 1924. Analyses and summaries of the returns of fuel consumption and units generated. la. 8vo. 11 pp. *London*, 1924

FICHTER, M. R. Les compteurs d'électricité. Préface de A. Mauduit. 8vo. 225 pp. *Paris*, 1920

FOWLER, F. H. Hydroelectric power systems of California and their extensions into Oregon and Nevada [Dept. of the Interior, U.S. Geological Survey, Water-supply paper 493.] 8vo. 1325 pp. *Washington*, 1923

FRITH, J., and BUCKINGHAM, F. Vibration in engineering. 8vo. 137 pp. *London*, 1924

GRUHN, K. Elektrotechnische Messinstrumente. 2e Aufl. 8vo. 223 pp. *Berlin*, 1923

HADFIELD, *Sir* R. A., *Bt.*, *D.Sc.* The metallurgy of iron and steel. Based mainly on the work and papers of Sir R. A. Hadfield. Compiled by the editor of Pitman's technical primers. sm. 8vo. 137 pp. *London*, 1922

HARVEY, G. M. Colliery electrical engineering. 8vo. 398 pp. *London*, 1924

HYDE, J. H. Lubrication and lubricants. sm. 8vo. 124 pp. *London*, 1922

HYDRO-ELECTRIC POWER COMMISSION OF ONTARIO. Rules and regulations governing electrical installations for buildings, structures and premises. Potentials from 10 to 5 000 volts. 7th (revised) ed. June, 1924. sm. 8vo. 213 pp. [*Toronto*], 1924

—— Notes *re* changes in "Rules and regulations governing electrical installations, etc.", appearing in the 7th (revised) ed. July, 1924. sm. 8vo. 25 pp. [*Toronto*], 1924

JAMES, W. Wireless valve transmitters. The design and operation of small power apparatus. 8vo. 279 pp. *London*, 1924

JOLLEY, L. B. W. Alternating current rectification. A mathematical and practical treatment from the engineering view-point. 8vo. 370 pp. *London*, 1924

JUMAU, L. Etude résumée des accumulateurs électriques. 2e édition. 8vo. 302 pp. *Paris*, 1924

KEMPTON, P. H. S. The industrial applications of X-rays. sm. 8vo. 125 pp. *London*, 1922

—— Industrial nitrogen. sm. 8vo. 116 pp. *London*, 1922

KOERTS, A. Atmosphärische Störungen in der drahtlosen Nachrichtenübermittlung. [Die Hochfrequenztechnik in Einzeldarstellungen, Herausgegeben von E. Nesper, Bd. 1.] la. 8vo. 162 pp. *Berlin*, 1924

KRAMERS, H. A., and HOLST, H. The atom and the Bohr theory of its structure. An elementary presentation. With a foreword by Sir E. Rutherford, F.R.S. 8vo. 223 pp. *London*, 1923

LAMB, C. G. Alternating currents. 2 pt. [bound in 1 vol.]. 8vo. *Cambridge*, 1921

LAMME, B. G. Electrical engineering papers. 8vo. 773 pp. *East Pittsburgh, Pa.*, 1919

LAWRENCE, R. R. Principles of alternating currents. 8vo. 446 pp. *New York*, 1922

LEBLANC, M., *fils*. L'arc électrique. 8vo. 131 pp. *Paris*, 1922

LECLERC, A. Manuel de télégraphie et téléphonie. sm. 8vo. 317 pp. *Paris*, 1924

LODGE, *Sir* O., *F.R.S.* Atoms and rays. An introduction to modern views on atomic structure & radiation. 8vo. 217 pp. *London*, 1924

LUCKIESH, M. Light and work : a discussion of quality and quantity of light in relation to effective vision and efficient work. 8vo. 312 pp. *New York*, 1924

MCFARLANE, W. Electricity in steel works. Describing current practice in the generation of electricity at steel works, the electric driving of rolling mills, the use of lifting magnets, and the electric lighting of steel works. sm. 8vo. 119 pp. *London*, 1921

MAGNUSSON, C. E., KALIN, A., and TOLMIE, J. R. Electric transients. 8vo. 201 pp. *New York*, 1922

MARIÉ, G. Traité de stabilité du matériel des chemins de fer. Influence des divers éléments de la voie. la. 8vo. 590 pp. *Paris*, 1924

AUTOMATIC AND SEMI-AUTOMATIC MERCURY-VAPOUR RECTIFIER SUBSTATIONS.

By G. ROGERS, Associate Member.

(*Paper first received* 1st *September, and in final form* 7th *October,* 1924; *read before* THE INSTITUTION 20*th November, before the* DUNDEE SUB-CENTRE 13*th November, before the* NORTH MIDLAND CENTRE 25*th November, before the* WESTERN CENTRE 1*st December, before the* SOUTH MIDLAND CENTRE 3*rd December, before the* IRISH CENTRE 11*th December; before the* MERSEY AND NORTH WALES (LIVERPOOL) CENTRE 15*th December, and before the* NORTH-WESTERN CENTRE 16*th December,* 1924; *also before the* NORTH-EASTERN CENTRE 12*th January, before the* SCOTTISH CENTRE 13*th January, and before the* TEES-SIDE SUB-CENTRE 5*th February,* 1925.)

SUMMARY.

The paper discusses briefly the principal features of the mercury-vapour rectifier, and describes a number of novel and successful applications of the use of automatic and semi-automatic mercury-vapour rectifier substations, designed for developing an efficient and economical direct-current supply to areas remote from existing sources of supply.

A method is given of feeding into an existing low-tension direct-current network by means of automatically controlled rectifiers for the purpose of improving the voltage and assisting already overloaded feeders. A specific case is considered, and the cost of three methods of dealing with this particular case is analysed.

The three methods considered are:—

(1) By means of new low-tension feeders from existing substations.
(2) By means of one new manually-operated substation and new low-tension feeders.
(3) By means of a number of automatic mercury-vapour rectifier substations.

Arrangements for the automatic and semi-automatic control are given, together with a description of the means adopted for automatically regulating the d.c. voltage.

A method of giving a d.c. supply at 550 volts to a 6-mile length of double-sleeper tramway track by means of semi-automatic rectifier substations is described, and complete details are given with the cost of one of these substations.

Sites and buildings for each of these types of substations are discussed, and general lay-outs are given, with special reference to simplicity, safety and cheapness.

TABLE OF CONTENTS.

(1) INTRODUCTION.

Electric supply authorities are being required to give a supply of electricity in their outlying areas for domestic purposes wherever it is demanded. Rapid development is taking place in town planning; building estates are springing up on the outskirts of our large cities, and are often far removed from available sources of supply. Whatever means are adopted to give a supply to these areas, a large capital expenditure has to be faced, the greater part of which is necessarily absorbed in the feeder and distribution mains. Since it is impossible to estimate the ultimate revenue likely to be drawn from the opening up of new districts, it is desirable to keep the initial expenditure down to the minimum. It would not pay to erect and equip a manually operated substation with costly low-tension feeders to supply a large thinly-populated area, and in such cases it will be found necessary to adopt automatic plant requiring the minimum amount of attention and labour, and to eliminate low-tension feeders where possible.

It is outside the scope of this paper to discuss the advantages and disadvantages of alternating-current versus direct-current supply, but it may be said that where available supplies have a frequency of 40 and over, the problem is simple, as distribution on the four-wire three-phase system is easy, cheap and flexible. The network may be developed where required, by means of static transformer substations, and the cost of a low-tension distributing system can be kept to a minimum. Direct current, however, has distinct advantages over alternating current for domestic supplies for cooking and power purposes.

On the other hand, where the supply is generated at 25 periods, a.c. supply at this frequency is, in the opinion of the author, unsatisfactory for domestic purposes and it becomes necessary to convert to direct current or to change the frequency by means of frequency-changers. Converting by means of rotary converters or any other form of rotary plant is too expensive for outlying districts, owing to the high costs of labour and the skilled attention required. Automatic rotary-converter substation equipments of small capacities will be too expensive. To put down one large automatic rotary-converter substation at some central point and feed out to considerable distances by means of low-tension feeders would prove very expensive, owing to the large capital that it would

be necessary to sink in copper. The obvious solution is to put down small automatic converting substations at points where the load is required, and to make them as near as possible comparable with the a.c. distribution mentioned above.

Greater Birmingham had to face the problem described above, and after preliminary investigations and tests the city electrical engineer, Mr. R. A. Chattock, decided to develop a system of small automatic substations equipped with mercury-vapour rectifiers of the glass-bulb type. This was a bold course to take, since there were not in existence any similar type of substations designed to give a three-wire d.c. supply. The series of substations described later in this paper were the first of their kind to be equipped in this country.

(2) The Principal Features of Mercury-Vapour Rectifiers.

The mercury-arc or mercury-vapour rectifier is an apparatus for transforming, statically, alternating current into direct current. The different forms of rectifiers now on the market are developments of the small glass-bulb rectifier introduced by Mr. Cooper Hewitt in the United States some 20 years ago.

The non-return valve action of the arc, when operating in a vacuum under certain temperature conditions, allows the current to flow in one direction only, viz. from the anode to the cathode, the cathode bath of mercury being the positive pole of the d.c. circuit.* An anode is provided for each phase of the current that is to be rectified. The negative d.c. pole is coupled to the star or neutral point of the three-phase a.c. transformer through a reactance.

Brown-Boveri Rectifier.

This apparatus has been fully described in the technical Press and is familiar to most engineers.

Vacuum.—The vacuum in the steel cylinder is obtained and maintained by means of a special exhaust pump. The extent to which the pump has to be used varies with particular sets. The pump of the set referred to in this paper has to be used only once a week when half load is not exceeded, but above half load it has to be continually in service.

Forming.—In this type of rectifier, after erection it is necessary for the anodes to be formed, and the operation of forming after the vacuum has been obtained takes approximately two weeks.† This process consists of heating up the anodes one by one by means of current passed through them to the cathode. The value of the current is gradually increased until something more than normal full load has been passed.

The effect is to eliminate any gases that might be given off from the material forming the anodes, which gases under working conditions might cause an internal flash-over or "backfire" due to the vacuum being temporarily destroyed on a portion of the surface of the anode. During this process the pump is kept working continuously. Current may be passed from the anodes to the cathode by means of a suitable resistance across the d.c. terminals of the rectifier or, better still, by means of some external source of supply such as a low-voltage booster. Again, if the set has been out of service for more than 24 hours it is necessary to re-form the anodes;* this operation takes about half an hour and must be done by manual operation. This is a drawback to this pattern of rectifier, which otherwise lends itself admirably to a simple form of automatic control.

Cooling.—Water cooling is adopted for the anodes and for the main cylinder, and this method is quite efficient. 70 gallons of water per hour are required for the set described in the paper. The apparatus has been found to be reliable in operation, and the maintenance costs are low.

Capacity.—Cylinders are now built each capable of giving up to 1 500 amperes (d.c.) at 600 volts.

Hewittic Rectifier.

This rectifier is of the glass-bulb type, the vacuum being permanent.

Cooling.—Fan cooling is adopted, the fan being placed under the bulb and blowing air across it. No special forming has to be done after delivery. Bulbs may readily be put into service almost immediately on completion of erection. Also, no forming is subsequently required, however long the bulb has been out of service. This is a very useful feature.

Life of bulbs.—The lower-voltage glass bulbs have a much better life than one would expect. Provided a bulb survives transit—and very few are damaged—and proves satisfactory in service for a few days, its life is extremely long.

The sealing of the incoming leads has been brought to a very high state of efficiency, and bulbs are still in service that have been running on load for over 8 000 hours—25 per cent of this period being on full load. The higher-voltage bulbs (460–600 volts) also give long service, but experience shows that they do not have such a long life as the lower-voltage bulbs. The percentage of failures is naturally higher.

Automatic operation.—The automatic operation and control of this type of rectifier is comparatively simple, and the particular cases dealt with in the paper indicate how readily they adapt themselves to this purpose.

Capacity.—Bulbs are now made each capable of giving 150 amperes up to voltages of 600. By arranging bulbs in parallel any capacity of plant may be obtained.

Short-circuits.—When a short-circuit occurs in the steel cylinder of the Brown-Boveri rectifier or in the glass bulb of the Hewittic rectifier when the vacuum fails, it is very severe. In both types of plant under the author's observation, however, short-circuits have been few in number, and in the case of the glass bulbs for 230 volts no single instance of a short-circuit has occurred.

(3) Automatic Operation and Control of a 220-kW Brown-Boveri Rectifier Working in Parallel with a Three-wire Battery for Balancing Purposes.

This type of mercury rectifier has been fully described in the electrical Press.† This set was first installed for manual operation, but later was equipped for auto-

* For further particulars see *Electrical Review*, 1921, vol. 88, pp. 217 and 251, and *Engineering*, 1923, vol. 116, pp. 507 and 543.

† By the latest method of forming this period is now reduced to 4–6 days.

* The latest plant does not require this process, and the disability referred to does not apply.

† *Loc. cit.*

matic control. It is connected to a 5 000-volt, three-phase, 25-period supply, and gives direct current at 460 volts across the outers of a three-wire network. Fig. 1 is a complete wiring diagram of the automatic

It will be seen that by means of selector switches the rectifier can be left running continuously on the system and, under these conditions, will be automatically disconnected from the busbars in the event of a fault

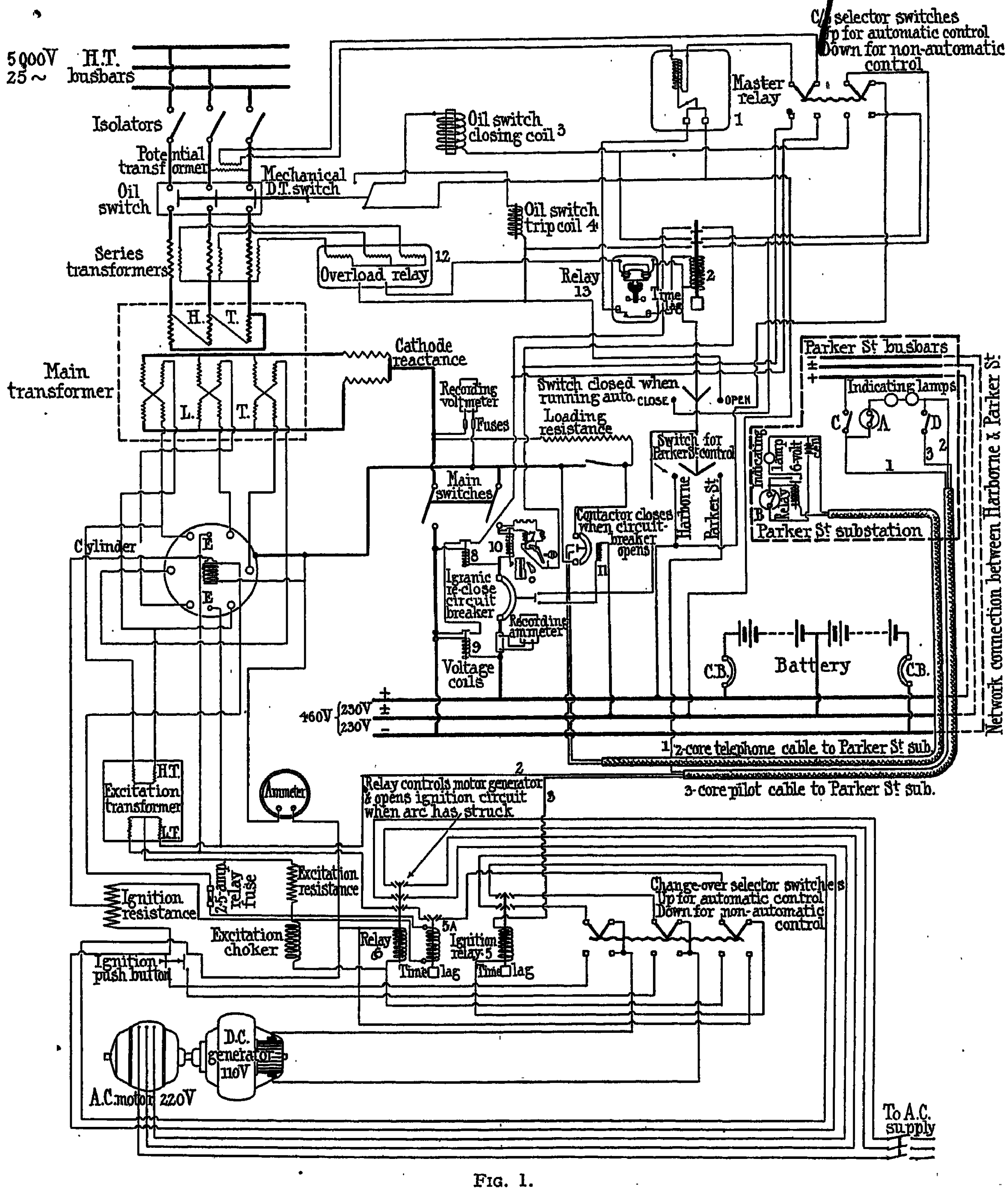

FIG. 1.

arrangements developed step by step until the necessary control was completed. The rectifier has been running now with this control for over two years, and no trouble whatever has been experienced with the set.

or a failure of the e.h.t. supply, and restarted as soon as conditions are again normal. It can also be arranged for remote control from another substation through pilot wires, in which case the rectifier can be started up and shut down at will, and while running will be auto-

matically disconnected and reconnected in case a fault develops, as in the first condition. By the simple addition of a voltage relay and a minimum-current relay, or by the addition of time switches, the set can be made entirely automatic in its operation.

The operation of the control gear is as follows, the action of the relays being described in their proper sequence of operation :—

(1) A master relay switch operated by the secondary of a potential transformer, which when energized closes the circuit operating relay (2) and, when de-energized due to failure of the a.c. supply, clears the set from the a.c. and d.c. busbars.

(2) A time-limit relay which, when energized, closes contacts operating oil-switch-closing solenoid (3) and, when de-energized, closes contacts which operate oil-switch-tripping solenoid (4). An interlock on this relay prevents the d.c. breaker from being closed or remaining closed when this relay is de-energized.

Immediately the oil switch closes, the pump and the ignition converter start up.

(5) The ignition relay which, when energized through interlocks on relays (5A) and (6), closes the ignition arc circuit. The action of this relay is delayed 10 seconds to allow the ignition motor-generator to become fully excited.

(5A) If the ignition arc fails to strike, this relay comes into operation and de-energizes (5), when the operation is repeated with an "in and out" movement until ignition is obtained.

(6) The coil of this relay is in series with the excitation circuit and operates immediately the ignition arc has been struck by relay (5). When energized, the relay shuts down the ignition motor-generator and de-energizes relay (5). The rectifier, after this operation, is ready for load on the d.c. side, and the d.c. breaker (an Igranic reclose circuit breaker) will now close and parallel the set to the busbars, provided that the voltage across the rectifier terminals is correct and the d.c. busbar voltage is not too high.

The closing coil of the d.c. circuit breaker is connected through an interlock on relay (2) and is also controlled by the adjustable voltage coils (7), (8) and (9).

(10) A series coil which opens the d.c. circuit breaker on overload. The operation of this coil is limited to three times, after which it remains open until reset by hand.

(11) A contactor which closes the loading resistance circuit when the d.c. circuit breaker opens.

(12) A three-phase inverse time-limit overload relay the operation of which shuts down the set.

(13) A relay which is operated by the action of relay (12) and prevents the oil switch being closed until reset by hand.

For remote control, the supply to relay (2) is provided by means of one core of a pilot cable through a control switch, and the coil circuit of ignition relay (5) is looped through pilot wires to a switch at the control substation.

The lamps shown on the control substation end clearly indicate :—

(1) When the oil switch closes or opens.

(2) When the excitation arc is struck.

The opening or closing of the d.c. circuit breaker is indicated by the low-voltage lamp connected to two cores of a telephone cable.

(4) Small Automatic Three-wire Rectifier Substations for Outlying Areas, Housing Schemes, Etc.

Fig. 2 shows an outline map of the Birmingham area, indicating the position of the generating stations, the existing manually-operated rotary-converter substations and the position of the rectifier substations in the outlying areas, each having its own distributing network.

These outlying areas are comparatively thinly populated. A 5 000-volt three-phase ring main passes through this area, looping into the various substations. Connections have also been made to other existing ring mains in the area.

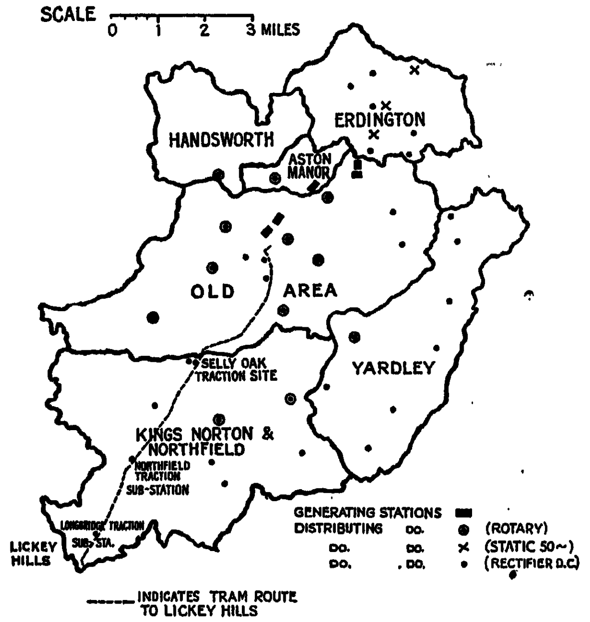

Fig. 2.—Map of Greater Birmingham, showing position of rectifier substations.

It was decided to commence operations with a three-wire unit having a capacity of 46 kW, the transformer supplying the two 23-kW rectifiers being designed for an ultimate load of 92 kW. Two 100-ampere 230-volt bulbs were connected in series across the outers of the three-wire network, the neutral or third wire being connected between them; and later, by the addition of two further bulbs of the same capacity in parallel, the unit was brought up to its full capacity of 92 kW.

Certain of these substations have already been brought up to the 92 kW capacity, owing to the rapid growth of the demand in these areas. Fig. 3 shows this development over a period of 12 months.

Provision is made in each case for an extension to the building when necessary. It is proposed to install in the extension a unit having a capacity of 138 kW, making the total capacity of each of the small substations 230 kW. This extra capacity has now been added in several cases and is likely to be enough for any particular area. When the full capacity of the

station has been reached, it is intended to develop areas in the district by means of further similar substations.

Lay-out of plant.—Fig. 4 shows the general lay-out of the plant in one of these substations. It will be seen that the dimensions of the substation have been kept

arrangements of the rectifier. It will be seen that the high-tension feeder is looped into the substation, the oil switches being non-automatic in operation.

The transformers, on the other hand, are protected by overload coils in each phase. Leakage protection is also provided by means of a current transformer in

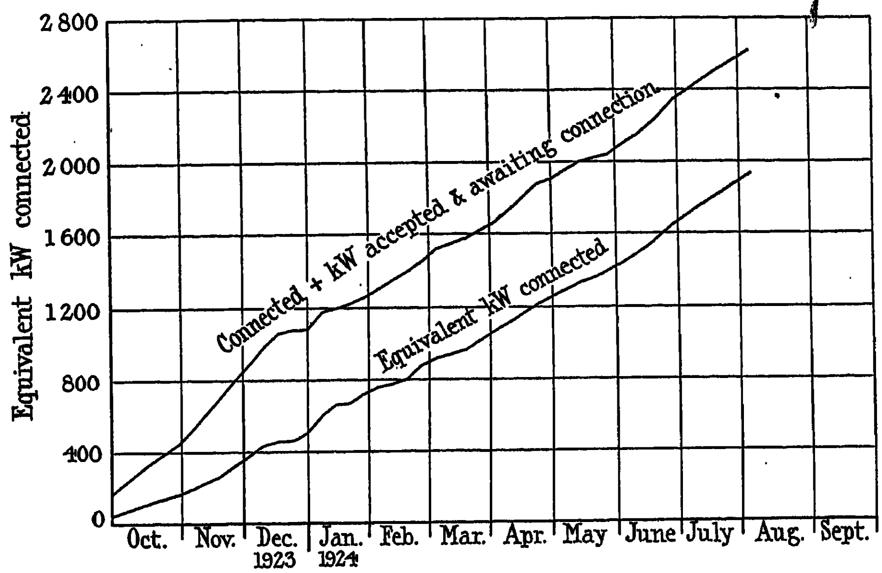

FIG. 3.—Curves showing progress of demand (mostly domestic load) in new districts opened up by means of rectifier substations.

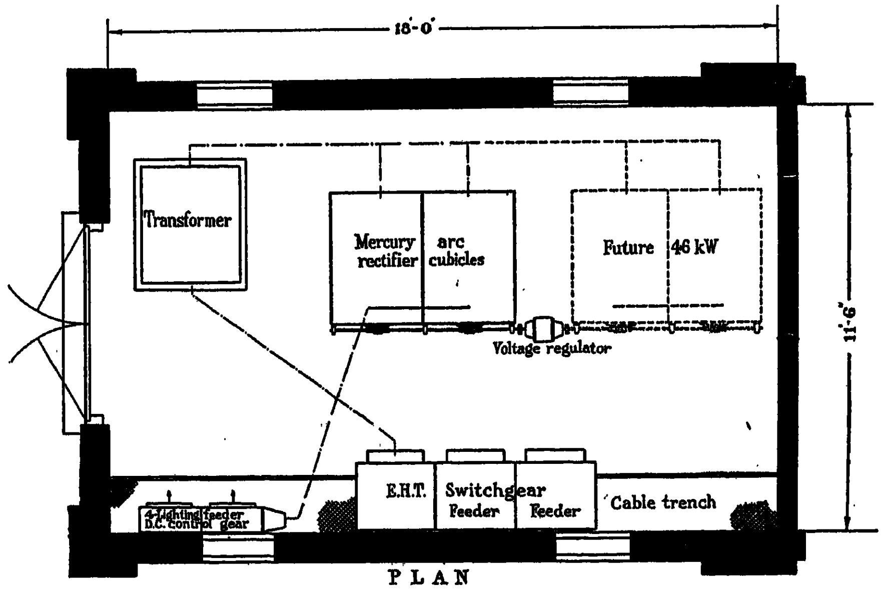

FIG. 4.—Lay-out of 46-kW 3-wire rectifier lighting substation.

as small as possible, due regard being given to ample passage ways and easy removal of the plant.

The rectifier cubicles are totally enclosed and no live parts are exposed. The high-tension and low-tension switchgear is also totally enclosed, and every care is given to provide safety and simplicity in operation.

Fig. 5 shows the general electrical connections in a complete substation, but does not include the internal

the "earth" connection of the transformer tank. A leakage of 2 to 3 amperes to earth is sufficient to cause the main oil switch to open. The current passing through the current transformer operates a special relay which, in turn, closes the trip circuit energized from the 230-volt circuit.

The rectifier itself is equipped with automatic gear which, in the event of a failure of the a.c. supply, will strike the ignition arc in the bulbs when this is restored,

and resume the supply to the external d.c. circuit. No automatic switchgear is provided on the d.c. side. Each connection to the distributing network is pro-

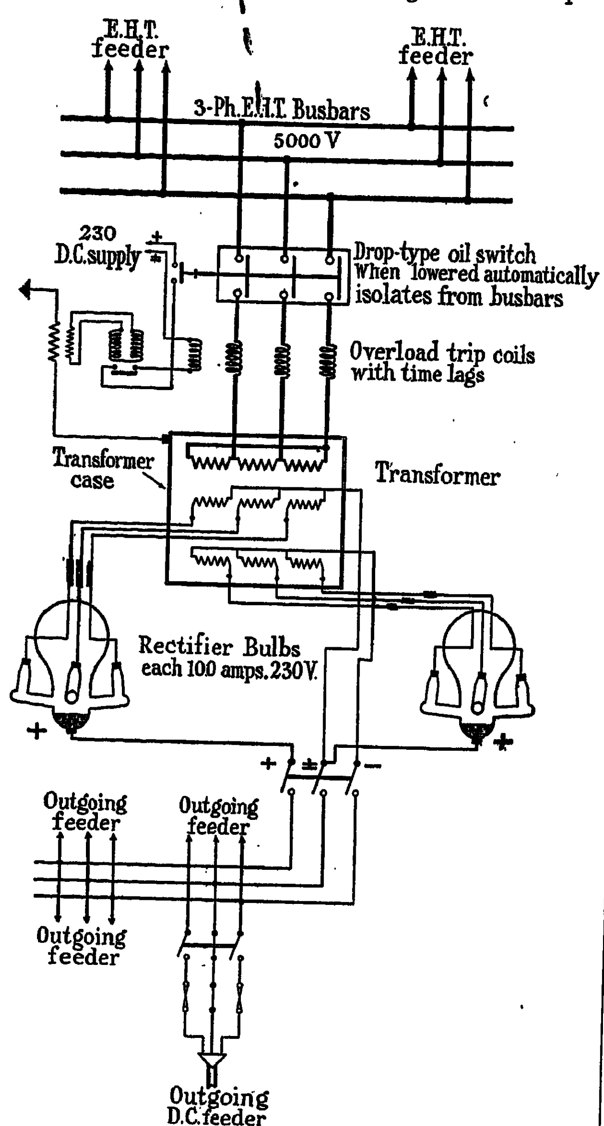

FIG. 5.—Diagram of connections of 46-kW 3-wire lighting and power rectifier substation.

tected by means of fuses. It may be necessary later to equip each of the rectifiers with a reclose overload circuit breaker, but up to the present it has not been found necessary on the small sets.

Efficiency and power factor.—The efficiency and power factor of a 92-kW three-wire rectifier equipment are shown in Fig. 6 (*a*). The complete cost of one of these substations, including plant, building, cabling and erection, is given in Appendix 1.

Cabling.—The cabling throughout is lead-covered, and the high-tension supply to the transformers is given by means of either a three-core armoured cable with the necessary sealing boxes at either end, or lead-covered single-core cables. All internal wiring and cabling of the rectifier equipment is of fireproofed cable.

Voltage regulation.—The d.c. voltage of a mercury-vapour rectifier is directly proportional to the a.c. voltage supplied to the anodes of the bulb. It follows, therefore, that in addition to the voltage-drop of approximately 5 per cent from no load to full load, there may be variations due to the variations in the a.c. pressure. If, as in this particular case, the ring-main feeder is fed from the same feeders that supply large power consumers, such variations may be fairly large. To meet this, an arrangement has been developed to operate the voltage regulator automatically. The rectifiers are provided with a regulating transformer having a number of tappings, and by means of sliding contacts the voltage of the supply to the anodes may be varied.

Fig. 7 is a facsimile of two voltage charts, one with no regulation and the other with the automatic voltage regulator in service. The electrical connections for the complete automatic control of the voltage regulator are shown in Fig. 8.

The operation of the automatic regulator gear is as follows :—

A voltage relay (1) connected across the d.c. terminals of the rectifier closes either of a pair of contacts at predetermined maximum and minimum voltages. The relay may be set to operate with any degree of closeness required.

The closing of either relay contacts energizes one of two solenoids (2), which in turn operates an arm carrying a set of contacts (2*a*). Each arm carries three contacts, two of which control the supply to the small operating motor (3) and are closed when the solenoid is energized, and one which short-circuits the armature of the motor when the solenoid is de-energized. The two solenoids are mechanically interlocked so that only one can operate at a time.

Each arm is also equipped with a time-lag (4) which prevents the operation of the motor due to a momentary change in voltage. The operation of one solenoid causes the motor to revolve in the forward direction,

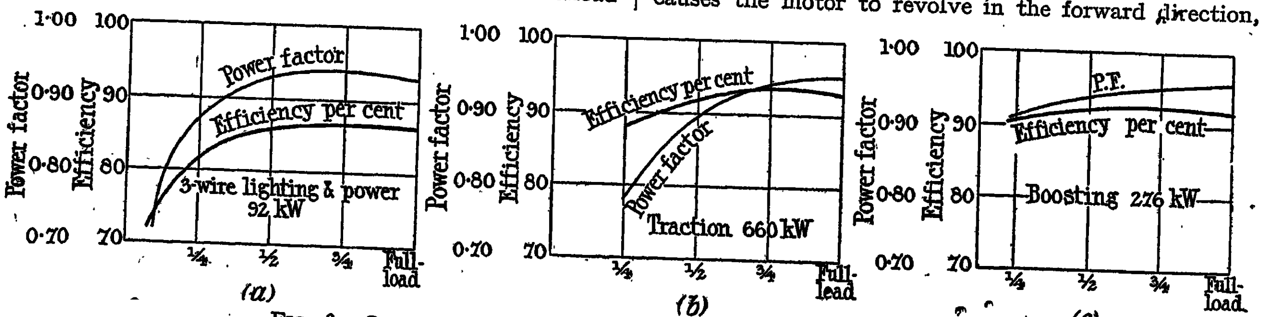

FIG. 6.—Curves of power factor and efficiency taken from tests.

and the operation of the other solenoid causes the motor to revolve in the reverse direction.

The motor shaft is connected directly to the operating spindle (5) of the regulator by means of worm reduction gearing. After either of the solenoids has been energized by the voltage relay, the motor continues to revolve until one complete revolution of the regulator spindle has been completed, whether the contact of the voltage relay (1) has opened circuit or not. At the end of each complete revolution the motor armature circuit is opened by means of a contact (6) on the spindle. If the contact of the voltage relay is still further closed, the motor will continue to make further revolutions, raising or lowering the d.c. voltage until the said contacts break the circuit.

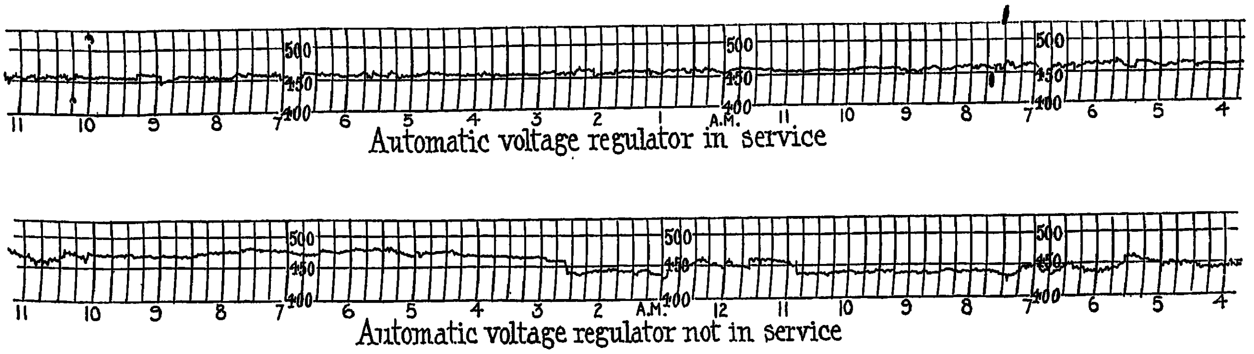

FIG. 7.

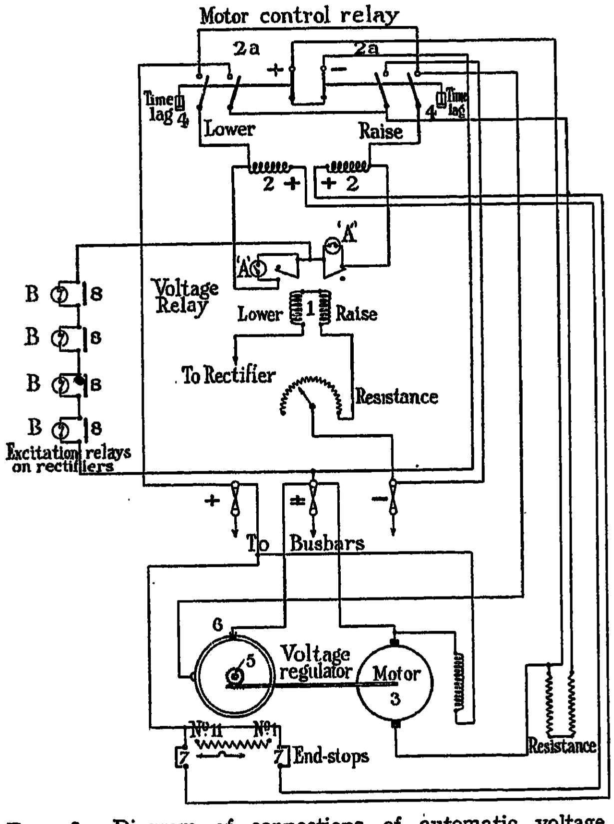

FIG. 8.—Diagram of connections of automatic voltage regulator (shown connected to one rectifier only).

End-stop switches (7) open the motor circuit by de-energizing solenoid (2) at the end of the travel to prevent over-running. The supply to the motor is so interlocked with the excitation relay (8) of each rectifier bulb that a failure of a.c. pressure or a failure of any one bulb opens the motor circuit.

Switches (A) are provided in the voltage relay circuits to allow of the operation of the regulator independently of the voltage relay, and switches (B) are also provided in the excitation relay circuit to close the interlock on any one bulb or pair of bulbs if not in service.

Suitable resistances are provided in the relay and operating motor circuits.

No attempt is made to balance the voltage of the two sides, care being taken to balance the external load as nearly as possible. It would be possible, however, to arrange for independent voltage regulation of the two halves of the three-wire set. Some 15 of these substations have now been put into service and the total capacity of the plant installed is approximately 1 850 kW.

Provision is made for earthing the neutral of the three-wire system at each of the substations. In practice two or more substations are in parallel through the network, the networks being connected solid on the neutral and through fuses on the outers.

(5) AUTOMATIC BOOSTER RECTIFIER SUBSTATION FOR FEEDING INTO EXISTING D.C. NETWORKS.

Many supply undertakings are now finding their existing d.c. feeders from the generating stations and rotary substations overloaded on the peak. Many of these feeders have been run out to considerable distances, with the result that when loaded up there is a big drop in voltage, necessitating the use of special boosters. The use of boosters is very inefficient, and to deal satisfactorily with large currents and big voltage-drops involves boosters which are very expensive pieces of apparatus. To deal with the load, it becomes necessary either to lay new feeders or to build and equip new substations. One method of solving this problem was described in a paper * read before the Institution by Mr. P. J. Robinson, of Liverpool. This method was to install automatic rotary-converter substations feeding direct into the net-

* *Journal I.E.E.*, 1923, vol. 61, p. 417.

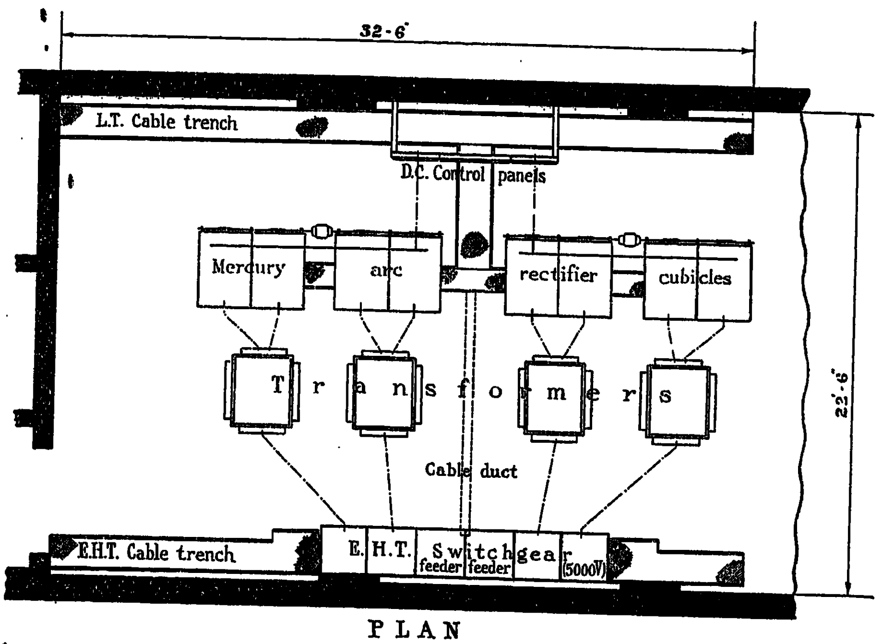

FIG. 9.—Lay-out of completely automatic substation consisting of two units each of 276-kW feeding into existing networks.

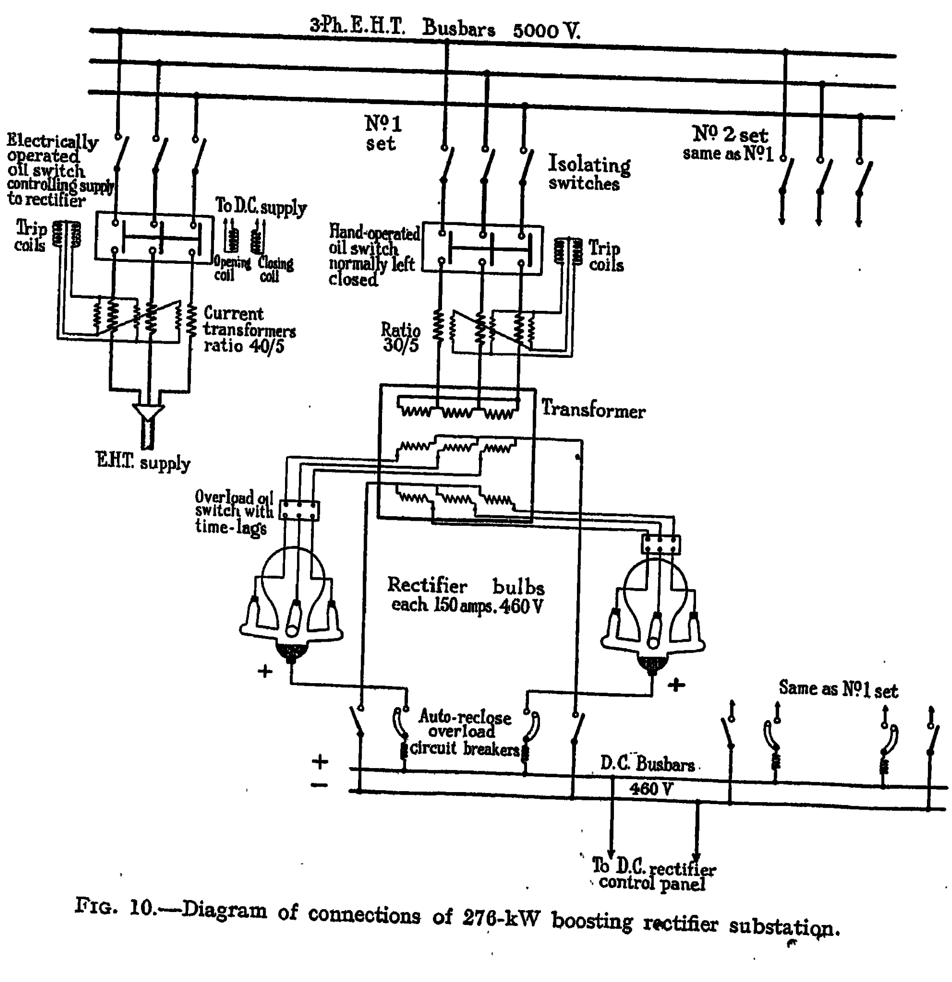

FIG. 10.—Diagram of connections of 276-kW boosting rectifier substation.

work at points of low pressure, and so to relieve overloaded feeders.

In Appendix 2 a particular case is taken, giving the estimated cost of three possible methods of dealing with the problem of overloaded feeders and bad pressures, and this shows a considerable saving in favour of the mercury-vapour rectifier equipment. It was decided to erect four small substations, each equipped with mercury-vapour rectifiers, having a capacity of 276 kW (that is, 600 amperes at 460 volts), feeding across the outers only, at a point in the network suitable for relieving the overloaded feeders and for improving the voltage. Each unit is made up of four 150-ampere bulbs (two per transformer) connected in parallel. In each case the overloaded feeder was 1 square inch in cross-section, and the rectifier substation was therefore capable of taking up

overload protection and recloses after a definite time interval when the overload condition is removed.

The method of starting up and shutting down the set as required is comparatively simple and follows the practice adopted for automatic rotary converters. It is, however, much simpler and requires a much smaller number of relays. The diagram of connections is shown in Fig. 11.

Starting Up.

(1) A master relay energized from a potential transformer across the high-tension supply which allows the following sequence of operations to take place only if the a.c. supply is normal. When the a.c. supply is normal, contacts (1*a*) are open. When closed the operation of relay (2) is prevented.

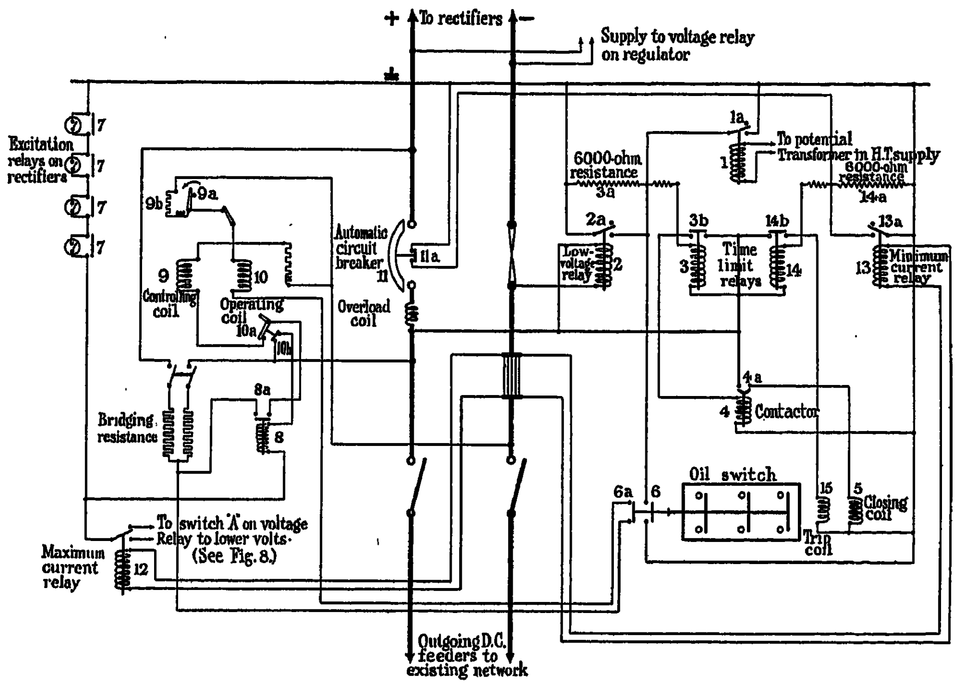

FIG. 11.—Diagram of connections for automatic control of one 276-kW 2-wire rectifier set.

approximately half-load on the peak. The plant in each of these substations is designed to be entirely automatic in its operation.

A typical lay-out of the plant in a substation containing two of these units is shown in Fig. 9; and the power factor and efficiency of one complete unit are shown in Fig. 6 (*b*).

The arrangement for controlling the voltage of the set is exactly the same as that already described for the small rectifier substations (Fig. 8).

Fig. 10 shows the main connections and the protective gear provided for each 276 kW unit. The e.h.t. supply to each transformer is controlled by means of a hand-operated oil switch provided with overload coils in each phase. These switches are normally left closed. The supply to the pair of transformers is controlled by an electrically operated oil switch, also provided with overload protection. The d.c. circuit breaker is provided with

(2) A voltage relay which opens contact (2*a*) when the voltage across the d.c. feeder falls to a predetermined value. The opening of contact (2*a*) de-energizes (3) a time-delay relay by inserting the high resistance (3*a*) in the relay coil. The contacts (3*b*) now close after a time interval (adjustable up to 5 minutes) which energizes (4) a contactor solenoid, causing the contact (4*a*) to close, which in turn closes the main oil switch supplying the transformer by energizing (5) the closing coil of the oil switch.

(6) An auxiliary switch which closes when the oil switch closes and which short-circuits the resistance (3*a*), again energizing the time-delay relay (3). The contacts (3*b*) open and the contactor (4) is de-energized, opening the closing-coil circuit. The transformer or transformers supplying the rectifier bulbs are now charged and the bulbs will tilt and strike the arc by the operation of the starting relays.

As soon as the excitation arc has been struck in all bulbs, the contacts (7) close. These contacts (one for each bulb) are in series, and can be short-circuited by (8a) close which in turn energize (9) the controlling coil of the auto-reclose circuit breaker. This circuit breaker is an Igranic reclose circuit breaker which is self-con-

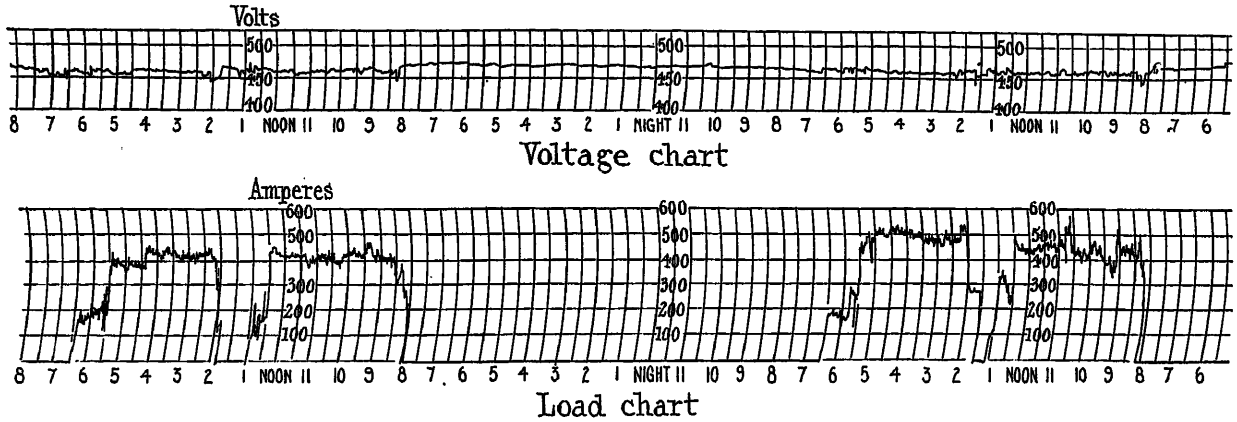

Fig. 12.

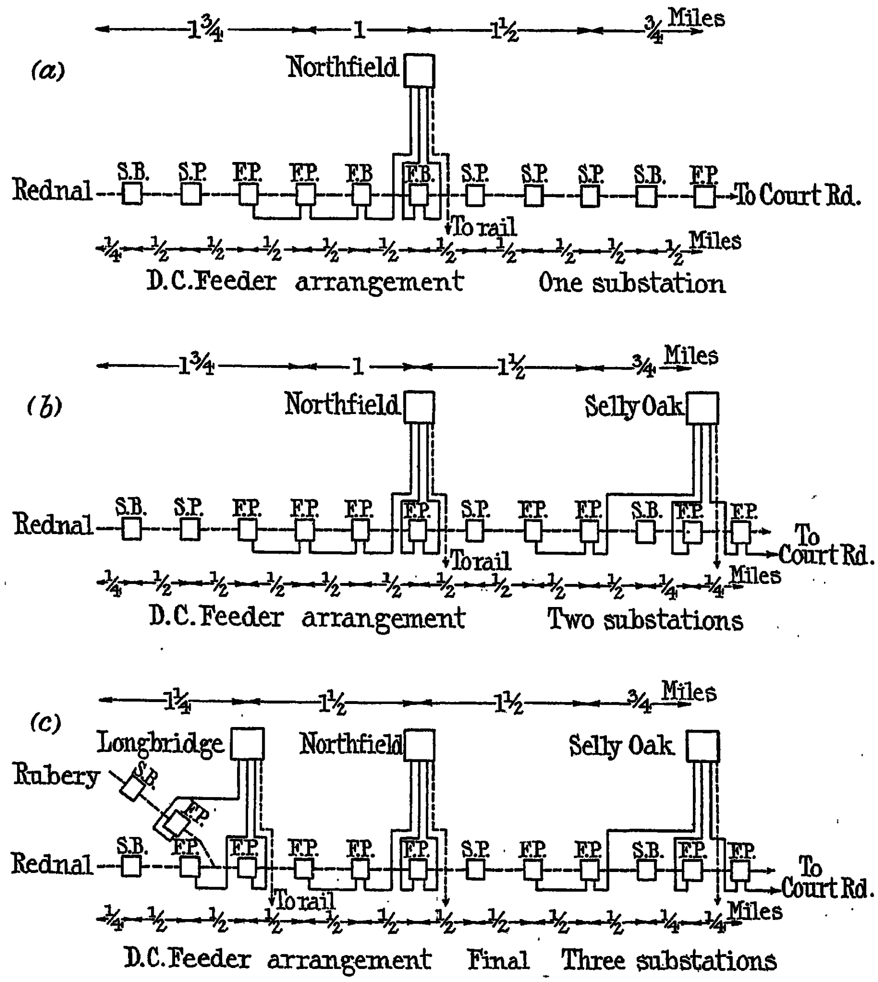

Fig. 13.

means of a switch in order that one or more bulbs can be cut out if not required.

(8) A solenoid relay is now energized and the contacts tained. Its function is to parallel the rectifier bulbs to the d.c. feeder supply. It is in the positive pole, the negative pole of the rectifier being connected to the

feeder negative through a knife switch and fuse. Its operation is as follows :—

The controlling coil (9), when energized, closes contacts (9*a*). This short-circuits the resistance (9*b*) and in turn energizes the operating coil (10) which closes the circuit breaker (11). The closing of the circuit breaker opens contacts (10*a*) and (10*b*) which de-energize the controlling coil (9) and the relay (8) respectively.

The operating coil of the breaker is also interlocked through contacts (6*a*) with the high-tension oil switch.

The voltage relay now comes into operation and adjusts the rectifier voltage to the particular setting of the relay. (The connections of the voltage regulator are shown in Fig. 8.)

A further relay (12), a maximum-current relay, comes into operation when the full load is exceeded, and operates to lower the voltage.

busbars and the d.c. positive circuit breaker is disconnected from the d.c. feeder, and the set will start up again when the d.c. voltage of the feeder falls low enough to operate the low-voltage relay (2), subject to the a.c. pressure being normal.

A typical load and voltage curve over a period of two days is shown in Fig. 12.

(6) Semi-Automatic Traction Substations.

An extension to the Selly Oak overhead tramway route from Selly Oak to Rednal and Rubery, a distance of approximately 5 miles (see Fig. 2), had to be supplied with current at 550 volts. The Selly Oak end of the existing route was about $2\frac{1}{2}$ miles from the nearest manually-operated rotary substation, and it was from this substation that the existing route received its supply.

Very heavy traffic was to be expected on this route at

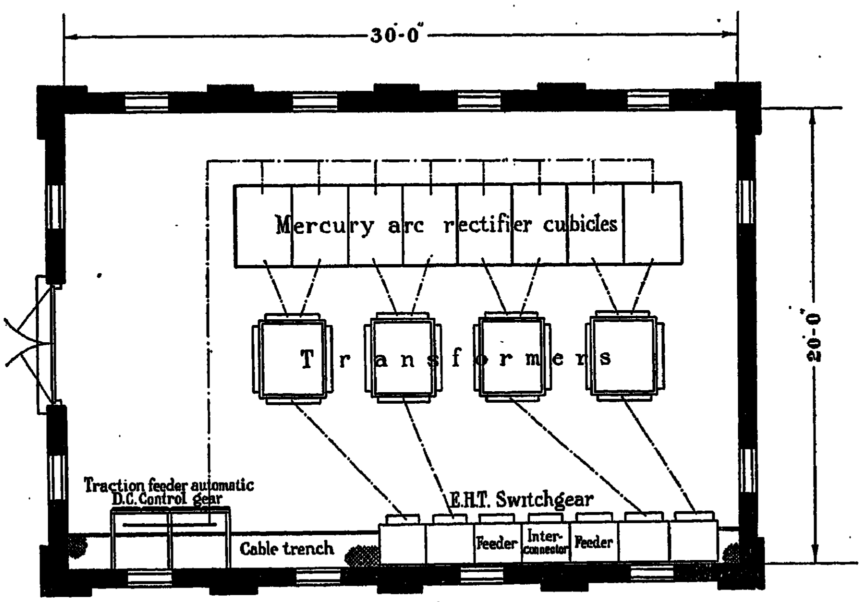

Fig. 14.—Lay-out of 660-kW rectifier traction substation.

The d.c. circuit breaker is set to operate on overload, reclosing after a definite time interval, provided that the excessive overload conditions are removed.

Shutting Down.

When the load falls to a predetermined value, relay (13), a minimum-current relay operated from a shunt in the feeder circuit, opens its contacts (13*a*) and de-energizes (14) a time-delay relay by inserting resistance (14*a*) in the coil circuit.

After a definite time interval, contacts (14*b*) close and energize (15) the trip coil, which causes the main high-tension oil switch to open.

The auxiliary switch (6*a*) opens when the oil switch opens and causes the d.c. circuit breaker to open.

Also, the opening of the d.c. circuit breaker closes the auxiliary contacts (11*a*), resetting the time-delay relay (14) by short-circuiting the resistance (14*a*).

The rectifier is now disconnected from the high-tension

holiday times and at week-ends during the summer, and it was necessary to provide plant and feeder cables capable of dealing with a half-minute service of cars. In addition to this holiday load, however, which would occur on only a comparatively few days in the year, there was a certain amount of rush traffic at certain times of the day. It will be clear, therefore, that for the greater part of the day and year a big proportion of the plant necessary to deal with the rush traffic would be idle.

It was obviously impracticable to supply the new route by means of new feeders run out from the existing substation, owing to the high cost involved. To build and equip a new manually-operated rotary substation somewhere on the new route would also have been prohibitive in capital and running costs. It was clearly a problem which admitted of only one solution, namely, automatic or semi-automatic plant which would require the minimum of labour and running charges.

After much consideration and comparison of the costs.

of various types of plant, it was decided to put down ultimately three substations, one at Selly Oak, one at Northfield, and one at Longbridge. Each of these substations has plant installed of a total capacity of 660 kW, making a total of 1 980 kW for the three substations.

Fig. 13 (*a*) shows the feeding arrangements when the Northfield substation was put in service. Fig. 13 (*b*) shows the second position when the Selly Oak substation was put into service, and Fig. 13 (*c*) shows the complete scheme with the three substations and the feeder arrangements from each substation. It will be seen that the negative return feeder is connected to the rails immediately outside the substation in each case. This arrangement enabled the cost of the d.c. traction feeder system and also the rail voltage-drops to be kept to a minimum, without undue expenditure on negative feeders.

The plant decided upon was the mercury-arc rectifier of the glass-bulb type. Each substation is equipped with eight rectifier bulbs, each giving 150 amperes at 550 volts. Each pair of these is supplied from one transformer, making use of the six phases of star-wound three-phase secondary windings. The complete unit of 660 kW capacity consists of four transformers, each supplying two bulbs in parallel. This arrangement gives great flexibility, since it is possible to run with any number of the bulbs in parallel. In the event of one transformer breaking down there is still 75 per cent of the plant available for service.

The high-tension supply to the substations is 25-period, three-phase, at 5 000 volts. The high-tension switchgear used is the same type as that used in the three-wire lighting stations. The lay-out of the plant in one of the substations is shown in Fig. 14. It is so arranged as to make the cabling as simple and as short as possible. All the rectifiers feed into a common positive busbar through Igranic reclose circuit breakers. The positive busbar is connected to the control panel for the low-tension traction feeders by means of cable. Each low-tension traction feeder is controlled by means of an Igranic reclose circuit breaker through a disconnecting switch of the knife pattern and a choking coil. This arrangement of control is shown in Fig. 15.

The control of this substation is only semi-automatic, it being the practice to leave the necessary number of sets running to supply the ordinary load and to switch in additional sets when required for extra load. The transformers are protected by means of series overload coils in the high-tension switchgear. Further protection for the transformers is obtained by means of a leakage relay placed in the earth circuit of the transformer. A small leakage of 2–3 amperes to earth from the transformer windings is sufficient to open the main oil switch.

The series overload coils are fitted with a time-lag which is so adjusted that in the event of any trouble on the d.c. side of the plant the low-tension switches would have a chance of operating first.

The low-tension secondary connections from the transformers to the rectifiers pass through special three-phase oil circuit breakers, also fitted with a time-lag. The d.c. Igranic circuit breaker in each rectifier gives further automatic protection in that it is designed to operate on overload and will reclose when the overload condition has been removed.

The main automatic features, however, are on the outgoing feeders themselves. The circuit breakers controlling these feeders are arranged to open instantly on a predetermined overload and will reclose after a definite time interval, provided that the overload conditions have been removed. These switches act perfectly and operate on overload or external short-circuits before

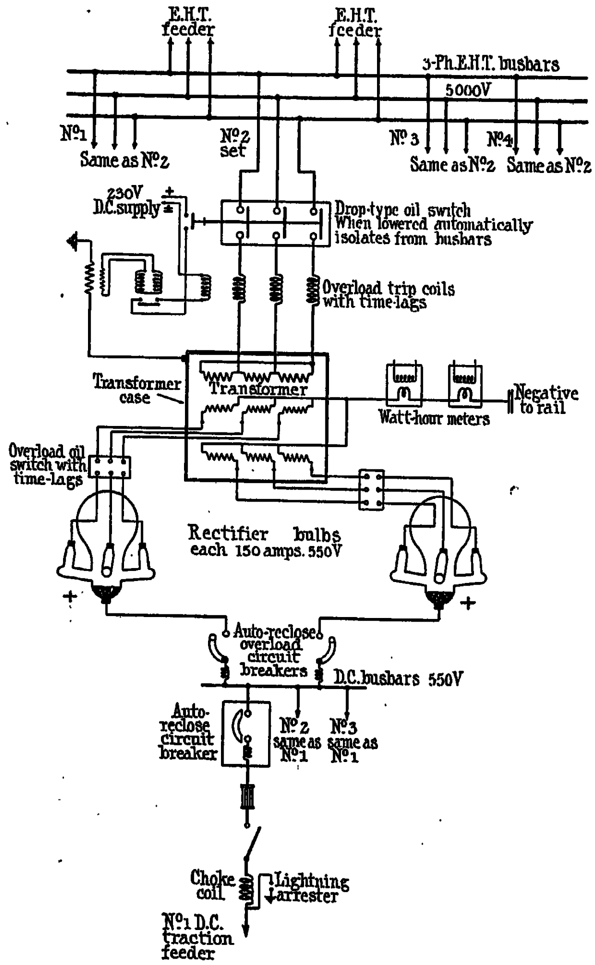

FIG. 15.—Diagram of connections for traction feeder substation (one set only).

any of the other protecting gear in circuit with the supply can operate. In the event of an overhead wire breaking down, the circuit breaker controlling the supply to that particular section will open and will not close again until the "earth" has been removed. Instantly the wire has been removed from the ground, the circuit breaker closes and the overhead wire is again made alive. Special instructions in this connection have been issued to the Tramway Department for the protection of their men.

In the event of a failure of the high-tension supply pressure, no switches will operate in the substation except the low-tension feeder and rectifier control switches if the station is isolated from any other supply,

and when the high-tension supply is restored the sets will automatically be started up and the supply restored to the d.c. feeders. This arrangement has up to the present worked perfectly satisfactorily, and every part has functioned correctly.

(7) Sites and Buildings.

Sites.—It is not a very difficult matter to obtain a suitable site for a comparatively small building on the outskirts of a city. Land belonging to the public authorities should first be exploited for possible sites; quite a fair percentage of the substations in Birmingham are erected on Corporation property belonging to other departments. Some are erected in the school playgrounds, and others in the grounds belonging to the Water Department. Failing a suitable site to be mutually arranged with other departments in this manner

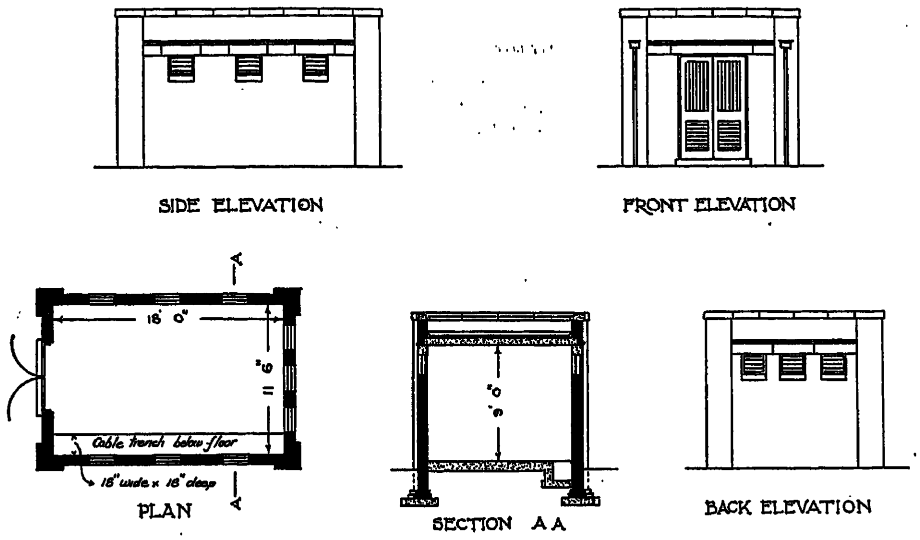

Fig. 16.—Standard 3-wire lighting substation.

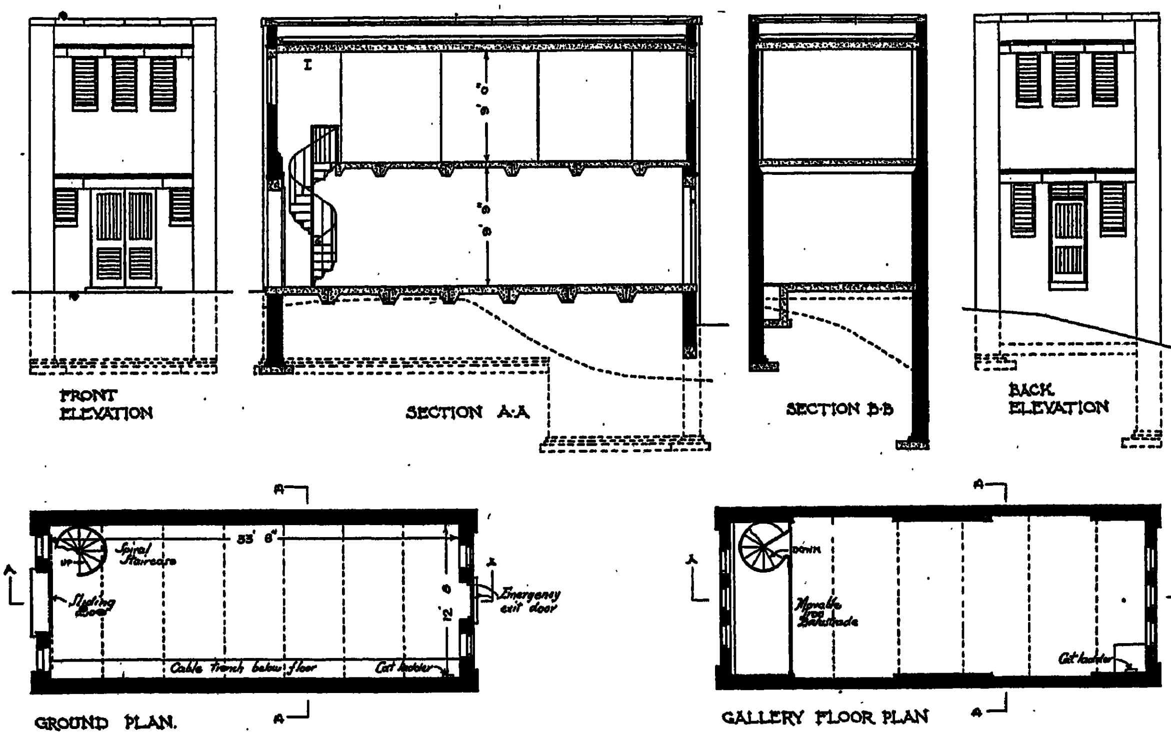

Fig. 17.—Two-floor boosting substation.

The power factor and efficiency of the traction rectifiers are shown in Fig. 6 (*c*). It will be seen that the efficiencies obtained are comparable with the efficiencies of rotary converters.

The total cost of one of these substations is detailed in Appendix 3.

it is possible, owing to the absence of noise from plant of this type, to buy or lease a small site, particularly when an area is being developed for building purposes.

In the city itself, however, a suitable site is often very difficult to obtain, and it may be necessary to adapt an old building or to build on an irregular-shaped site for the purpose of housing the rectifier plant. Some ingenuity and patience has to be exercised in this respect. The principal requirements of a site are suitability of access for plant and cable ways.

Buildings.—In designing buildings for this particular class of work, it must be borne in mind that simplicity, cheapness and freedom from fire risks must be the principal factors. There will be no attendants in these stations, and it is not necessary to have any idle floor space in the building. The plant does not require any lifting tackle, the transformers being mounted on wheels.

In most cases the question of appearance of the building and its relation to surrounding property in residential areas has to be considered. Many of the substations described in the paper had to be specially designed from an architectural standpoint to suit the wishes of the owners of surrounding property, and, of course, in every case to satisfy the city surveyor. Further, the bye-laws relating to buildings have to be observed, and it is therefore wise to put the design of new buildings of this kind in the hands of a good architect who will arrange to satisfy the many interested parties.

The peculiar light from the bulbs, and the flicker due to the rotating arc, make it advisable to prevent any direct light from the substation being seen outside. One way of doing this is to provide V-shaped louvres in the walls of the substation.

A suitable cable trench to bring in the necessary cables and suitable drainage from the roof for storm water must be provided.

Usually, a single-floor building is most suitable, but where the ground space available is small a two-storey building can be readily adapted for this purpose, the transformers being placed on the ground floor, and the rectifiers and switchgear on the first floor.

Ventilation.—Efficient ventilation can be obtained by means of the V louvres in the walls and doors of the substation, and by the provision of suitable roof vents.

Typical standard three-wire lighting substation (Fig. 16). —These buildings are erected with 9-in. brick walls strengthened at the corners with external piers 4½ in. thick and about 2 ft. wide. The inside of the walls is faced with ordinary common bricks having neat flush joints. The outside facing work is carried out with varying coloured Black Country bricks having white cement joints. Artificial stone is employed for the copings, which are weathered and throated, and similar stone for the heads to openings above doors and ventilators, these heads being slightly reinforced with steel bars.

The floor is formed with cement concrete 8 in. thick, reinforced with expanded metal and finished with a spreading of granolithic. The cable trench is also formed with concrete, similarly reinforced, the trench being covered level with the floor with chequered iron plating on iron curb and supports.

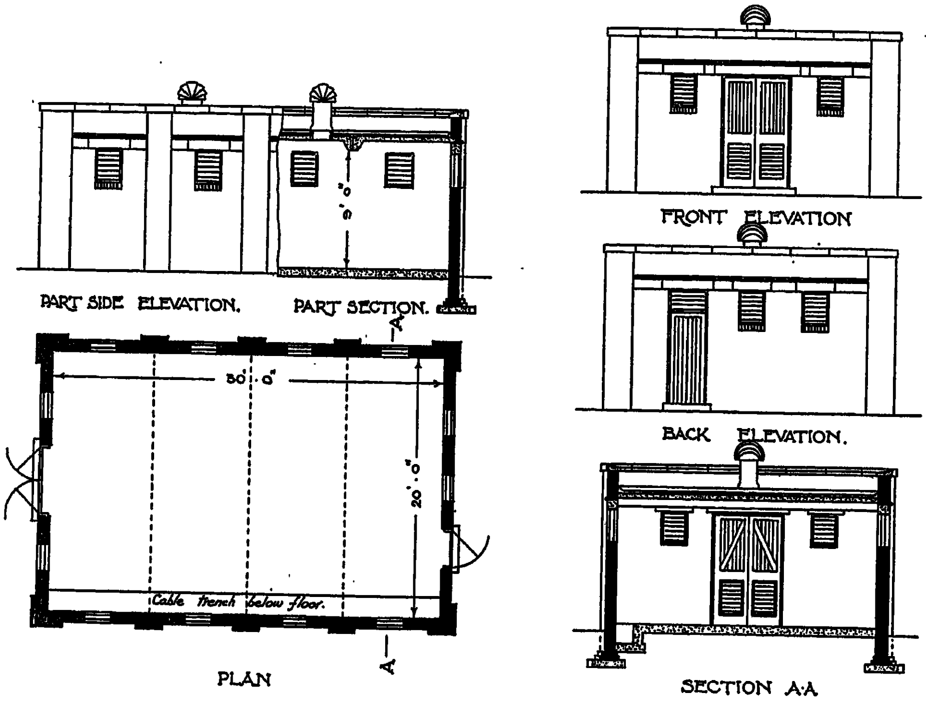

FIG. 18.—Traction rectifier substation.

The flat roof is formed with Seigwart pre-cast hollow beams, having on the top a screeding of cement laid to falls and covered with asphalte. The underside of the Seigwart beams has a fair face and no plastering is therefore needed, the joints being merely pointed with cement. This method of roof construction forms a very suitable fixing for cables and wires.

The ventilators consist of louvres in a frame, the louvres taking the form of an inverted " V," in order to allow a free passage of air and at the same time forming a screen to prevent the direct rays of strong flickering light penetrating to the outside.

The doors are framed, ledged and braced, the upper panels being filled in with narrow matchboards and the lower panels formed into louvre ventilators of similar construction to the above.

Typical two-floor substation (Fig. 17).—The station illustrated has been erected upon a narrow site having road frontage at either end, and the ground being bad it was necessary to carry the foundations deep. The construction of the walls is similar to that in the other stations, the flat roof being formed with Seigwart beams.

The ground and gallery floors are formed with suspended reinforced concrete, the latter floor being trimmed to form an opening, and a rolled steel joist is provided over this opening for hoisting the machinery to the gallery floor.

An iron spiral staircase is provided to give access to the gallery floor, and a cat ladder at the other end to serve as an exit in case of fire.

The doors are similar to those described for the other stations, except that the main entrance doors in this case are hung to slide in order to give clearance to the staircase.

Typical traction rectifier substation (Fig. 18).—These stations are erected in a similar manner to the lighting substations, the main difference being in the construction of the roof which, owing to the length of the span, is formed with suspended concrete reinforced with rolled steel joists and expanded metal. A small door is introduced into these stations to serve as an emergency exit in case of fire.

(8) Conclusion.

The author makes no claim that the type of rectifier substation described in this paper is complete or in final form, but takes the view that in each case an attempt has been made, with some success, to develop and use new plant for special purposes, to the end of reducing costs of development.

Attempts have been made to discriminate in each case the automatic features essential for the successful operation of the gear. It is possible to carry automatic control to almost any extent of completeness, but this only adds to the complexity of the switchgear and also increases the cost.

The author would like to express his indebtedness to Mr. R. A. Chattock, the city electrical engineer, for his kind permission to publish the information contained herein, and to his assistants, Mr. Thurman and Mr. Deeming, for their help in preparing the various diagrams included in the paper.

APPENDIX 1.

Cost of One 92-kW Three-wire Lighting Rectifier Substation.

The following is the detailed cost of a standard three-wire rectifier substation containing plant of 92 kW capacity, two high-tension feeder switch panels, one transformer high-tension switch panel, and low-tension iron-clad switchgear for controlling four outgoing three-wire low-tension distributors.

The costs include all the interconnector cables between the high-tension oil switch and the transformer, between the transformer and the rectifier, and from the low-tension side of the rectifier switchgear to the distributing gear.

The costs also include all labour charges and sundry materials.

	£
Cost of 92-kW 3-wire rectifier plant	1 478
E.H.T. switchgear, two-feeder panels, and one transformer panel	130
Low-tension d.c. switchgear	32·65
Automatic regulating gear and switches and resistance for B.O.T. earthing panel ..	85
Cabling	45
Labour costs for erection	40
Total	£1 810·65

The cost of the substation building for housing this plant, including cable trench, chequer plating, drainage, fencing, etc., is £320.

APPENDIX 2.

Automatic Boosting Stations.

It was necessary to relieve the load on four existing low-tension feeders in the Central City district. The areas concerned were at considerable distances from any of the existing stations or substations, and each of these feeders required boosting at the supply end.

The estimated costs of three alternative means of supplying this load are given as follows:—

(1) *By means of new low-tension feeders, from existing substations.*

Capital cost.	£
Cost of 4 × 1 sq. in. l.t. feeders	21 360
Sundry sub-feeders and linking-up mains ..	1 515
Additional rotary converter and booster capacity required, in existing substations	7 200
E.H.T. and l.t. switchgear	1 600
	31 675
Add 10 per cent for contingencies	3 167
Total	£34 842

The estimated annual running costs would be as follows:—

	£
Interest and Sinking Fund	2 803
Value of units lost in conversion and distribution, at ½d. per unit	760
	£3 563

(2) *By means of one new manually-operated substation and new low-tension feeders.*

	£
Estimated cost of building	2 000
Three 500-kW rotary converters	9 000
E.H.T. switchgear	800
D.C. switchgear	900
Internal cable connections	300
Cost of e.h.t. feeders and four l.t. feeders ..	13 890
Sundry sub-feeders and linking-up mains ..	1 515
	28 405
Add 10 per cent for contingencies	2 840
Total	£31 245

Annual running costs.

	£
To operate this substation two shifts of two men each would be required. The annual cost of wages would be	650
Value of units used for lighting	10
Value of units lost in conversion, at ½d. per unit..	360
Maintenance of plant	150
Loss in l.t. feeder cable, at ½d. per unit.. ..	200
Interest and Sinking Fund on plant, switchgear, cables, etc.	2 370
Interest and Sinking Fund on buildings ..	160
Total	£3 900

(3) *By means of a number of automatic mercury-vapour rectifier substations.*

	£
Estimated cost of four substation buildings at £400 each..	1 600
Four 276-kW rectifier equipments	8 986
E.H.T. switchgear	900
L.T. switchgear, including automatic control features, voltage regulator, etc.	1 400
Internal cable connections	200
Cost of e.h.t. cables and l.t. feeder cables ..	2 200
Sundry sub-feeders and linking-up mains ..	1 515
	16 801
Add 10 per cent for contingencies	1 680
Total	£18 481

Annual running costs.

	£
Value of units lost per annum in rectifier equipment and distribution, at ½d. per unit ..	360
Annual maintenance of bulbs and plant ..	150
Labour	200
Interest and Sinking Fund on buildings, plant, etc.	1 545
Total	£2 255

SUMMARY.

	Capital cost.	Annual cost.
Scheme 1	£34 842	£3 563
Scheme 2	£31 245	£3 900
Scheme 3	£18 481	£2 255

It will be interesting to compare the estimated cost of one of these substations with the actual cost.

The actual cost of one of these substations equipped with an automatic boosting set of 276 kW capacity is as follows :—

	£	s.	d.
Building	951	0	0
One 276-kW rectifier equipment	2 278	0	0
E.H.T. switchgear	218	0	0
D.C. switchgear, including automatic control and voltage regulator	361	11	10
Internal cabling	50	5	10
Cost of erection	168	5	2
Total cost of building, plant and erection	4 027	2	10
E.H.T. feeder extensions and l.t. feeder, etc...	1 120	0	0
Total	£5 147	2	10

It will be noticed that the cost of the building is much more than that allowed for in the estimate, but the building is large enough to house another similar equipment of larger capacity.

APPENDIX 3.

The following is the cost of one of the traction substations containing 660 kW of rectifier plant. The costs include two e.h.t. feeder switch panels, one busbar coupler switch, four e.h.t. transformer switch panels, the necessary automatic switchgear for controlling the supply to three low-tension traction feeders, the necessary cabling and the cost of the complete erection of the plant.

	£	s.	d.
660-kW rectifier plant complete	4 858	0	0
E.H.T. switchgear	323	0	0
D.C. switchgear and meters	181	0	7
Cabling, etc.	126	13	0
Cost of erection	168	9	0
Sundries	35	5	2
Total	£5 692	7	9

The cost of the building, including drains, fencing, etc., to house the above plant, which also provides space for the switchgear and plant for a complete 3-wire lighting unit of 92 kW capacity, is £480.

DISCUSSION BEFORE THE INSTITUTION, 20 NOVEMBER, 1924.

Captain J. M. Donaldson: The reason for using direct current at Birmingham is stated in the early part of the paper, but in view of the author's statements I think that the question of alternating current ought not to be put lightly on one side. As a matter of interest I have taken out a few figures showing what it really means from a financial point of view. On page 171 the cost of a rectifier substation with a capacity of 92 kW is given as something of the order of £1 800 exclusive of the building and exclusive also of the land on which the building is erected. That works out at about £20 per kW. I have taken out the figures for a little substation containing two 50-kW transformers, and the cost comes out at rather under £400, or about £4 per kW. The same building could easily take two 100-kVA transformers, and the cost would not be much more than £500, or £2 10s. per kW. Of course, that is rather a considerable item, and as a matter of fact it is not the only additional expense, because owing to the lower efficiency obtaining with a rectifier substation—of the order of about 10 per cent—the feeders have not quite the same usefulness that they have in an alternating-current system. The author rather infers that the question of pressure regulation is very difficult with static substations. I think that most people with experience of such substations do not find that difficulty; but in any case it is just as easy to meet it in a static substation as it is in a rectifier substation. In other words, a regulator similar to, though possibly on a different principle from, the one described by the author will do precisely the same thing if required. The overload capacity of a static transformer is considerable, but I think I am right in saying that mercury-vapour rectifiers will only take an overload of about 20 per cent for a few minutes. It is only fair to say, however, in comparing prices, that one of the reasons for the high cost is that two tubes are used in series in order to get the middle wire. It makes very little difference to the cost of the rectifier tube or bulb whether the pressure is 460 or 230 volts, but this device for obtaining the middle wire adds greatly to the expense. The other disadvantage of having the two tubes in series is, according to my estimate, that the efficiency is undoubtedly reduced by about 4 or 5 per cent, because the loss in the arc is a fixed amount—about 20 volts—and this is doubled when two tubes are in series. The efficiency as shown in Fig. 6 (*a*) is of the order of 87 per cent on the little 92-kW sets, and I do not think there would be any difficulty in getting an efficiency of 97 per cent or more in a static substation. The author compares the steel-tube (or Brown-Boveri) rectifier with the glass-bulb rectifier. I hold no brief for either, but I do not think that he has been quite fair to the steel-tube type. It would certainly appear from Fig. 1 that it is very complicated. I should like to know whether the ignition is still started mechanically in the glass-tube rectifier, as I imagine it is, or whether, as in the case of the steel tube, a separate ignition circuit is needed. I should also like to know why Birmingham, one of the pioneers in the use of the Brown-Boveri rectifiers, gave them up. Three sets of efficiency figures are given in the paper; one for the three-wire 92-kW set, one for a 276-kW booster, and one for a 660-kW traction set. It will be noticed that the traction and the booster sets, which are single-tube, have a very much higher efficiency, for the reasons I have already indicated, and also because in the traction set the voltage is higher. Were the efficiency curves obtained experimentally by the author's staff, and, if so, were they obtained by indicating instruments or by integrating instruments? The reason for my asking is that I do not think the two methods give the same results. My own impression is that integrating instruments undoubtedly give a very much lower value than do indicating instruments. To my mind, the integrating test is really the practical one. I believe that the reason is the rather curious wave-shape, and the fact that only one side of the wave is used. The main objection to the rectifier as a converting device is the question of regulation. The author refers to a figure as low as 5 per cent, but I do not remember getting anything as good as that. With the Brown-Boveri rectifier the figure is of the order of 9 per cent in order to keep the pressure up, and I have found it necessary to install an induction regulator in addition. The regulating device described in the paper appears to be a sort of booster transformer having a variable number of turns which can be cut in or out as the case may be. I should be glad if the author would give some additional information with regard to that point. As to the question of ripples, the Post Office maintains that a change-over from alternating to direct current increases the interference, and does not exonerate even rotary converters from blame. I rather think, however, that the ripples in the case of the mercury-arc converter are more pronounced than those due to rotary converters.

Mr. W. E. Highfield: The paper is really a study of one means of supplying the network of a 25-period three-phase system. I think that both in England and abroad the tendency has been in the direction of making the network 50- or 60-period, three-phase, and I do not think anyone would seriously state that that system is not the best; the reason being, of course, that the static transformer makes it very flexible and efficient. It is thought unorthodox to consider lighting at anything under 40 periods, and phase-changing is practically impossible on account of the cost. In other words, it is a very inefficient system, and it seems to me to be certain, in view of the number of 25-period systems in this country, that the d.c. networks will be extended. The author has put forward a very strong case for the mercury-vapour rectifier for certain specified cases; and, judging it both from the financial side and from the technical side, I do not think that that position can be seriously attacked. The mercury-vapour rectifier is the nearest approach to the static transformer that has been produced, and an apparatus that has no moving parts has a very great advantage over one that

has to revolve. The rectifier may not be in its perfected form, but it is good enough and there are bound to be improvements as its application goes on. One matter that is not mentioned in the paper, but which was referred to in one form by Captain Donaldson, is the fact that any form of rectifier introduces a harmonic into the primary. It is due to the difference between the primary and secondary wave-forms, and it is inherent in the system. The result is that the primary may suffer from over-voltages unless steps are taken to filter out the harmonics. It should not arise at Birmingham, because the primary voltage is low and rotary-converter substations are run in parallel on the same network, and the rotary converter is a very fine means of filtering harmonics. I feel sure that on any system employing rectifiers alone, and especially on those at extra high tension on the primary side, there will be considerable trouble due to harmonics introduced on the primary and possibly reflected on the secondary. The substations on the Midi Railway contain plant of both types. The d.c. voltage is 1 500, and the frequency is 50. The rotary-converter units are each of 1 000 kW. The rectifiers are of 1 200 kW capacity and are of the Brown-Boveri type. Both types of plant have given minor troubles, but I do not think there have been troubles to which any engineer could reasonably object, especially considering the novelty of the plant. Of course, there is a great difference between being in a rotary-converter substation and a rectifier substation. In the case of the former, if anything happens on the line a large load will be thrown on the station. A severe short-circuit outside the substation will probably cause a flash-over, and there will be a loud noise, but the energy will be dissipated without very much damage. The machines can be run up immediately. Now in the rectifier substation it is quite different. There is hardly any noise; nothing is heard except the air pump, and if a short-circuit occurs outside it is the linesman and not the substation attendant who has to attend to it. The rectifier is not affected by the short-circuit, but the harmonics it introduces into both primary and secondary circuits may cause, and do cause, breakdowns on the lines.

Mr. A. M. Taylor: In the cases referred to in sections (2) and (3) of Appendix 2, the showing is distinctly in favour of the rectifier substation. The reason why no spare rectifier bulbs are included in the estimate for the four substations is that each substation is virtually in parallel with the other three substations, under the particular circumstances of the area to be supplied. As regards the estimate in Appendix 1, I do not think that the author has made out a convincing case for using rectifier substations of very small capacity for very scattered areas. Owing to the fact that a neutral wire has to be supplied, each rectifier bulb must give only 230 volts. This involves a low efficiency and a very high capital cost (£16 per kW). I am not sure whether, in the case of an existing 25-period supply having to be extended into the sparsely populated districts, the method of supply devised by Mr. J. R. Beard might not with advantage be employed. No doubt the use of a static frequency-changer to inject a triple-harmonic E.M.F. into the neutral wire is a disadvantage, but under Mr. Beard's proposal it would be quite possible to arrange that the output of the frequency-changer was only about 1/9th to 1/15th of that of the substation. Hence, with an efficiency in the frequency-changer itself of only 85 per cent, the average efficiency of the whole substation may be considered to be equivalent to 96 per cent. Similarly, the cost of the frequency-changer is reduced to the equivalent of only, say, £1 per kW for the whole substation. The regulation of the frequency-changer designed by myself is 6 to 8 per cent, and therefore compares quite well with the inherent regulation of the rectifier. The power factor, it is true, is very low indeed (20 per cent), but if only 1/9th to 1/15th of the whole output of the substation has to be provided by the static frequency-changer, the total current supplied to the substation over the underground e.h.t. feeders is only increased by 50 to 33 per cent. Now the extra capital outlay, due to stiffening up the e.h.t. feeders to compensate for this, is only some 5 to 7½ per cent—quite a negligible amount. The low power factor is thus compensated for. The above argument is based on the assumption that, by employing Beard's method of supply, the cooking and heating and motive power load can be differentiated from the purely lighting load, which is the only one adversely affected by the low frequency.

Mr. H. Brazil: One or two speakers in the discussion have made a point of these rectifiers having to be run two in series, with the resultant loss of efficiency. This, of course, is quite correct if it is desired to balance, but even then it is not necessary to have all the bulbs two in series, as one or two sets can be balancing bulbs, and the rest may be put across the outers. It will be seen, therefore, that the objection that has been raised as to their inefficiency because two must be in series, is not entirely correct. The company with which I am connected was faced with the problem of compensating for a very heavy voltage-drop at two outlying points. The cost of providing additional copper in the low-tension feeders was prohibitive, and it was essential that the supply should be direct current in parallel with the existing network. When on a visit to Birmingham I saw several of the rectifier substations installed there, and was much impressed with their great simplicity, with the ease with which they were started up, and with their capacity for overload. As a result of what was seen there we have erected two rectifier substations which will be working shortly and will deal with the problem mentioned above. I feel sure that in cases of this sort, where a comparatively small amount of current is required at the point where the pressure is low, these glass-bulb rectifiers will be extremely useful, but on the other hand it seems clear that they cannot take the place of the main substations where the current demand is heavy. This is particularly the case where the declared pressure is low, as, owing to the fact that the capacity of the bulb decreases with the voltage, the number of bulbs required would be too great to be practicable.

Mr. S. C. Bartholomew: I had hoped that the author would have told us what steps are being taken to avoid interference with Post Office communication circuits. I was pleased, therefore, to hear Captain

Donaldson raise the question. The use of mercury rectifiers for supplying current to the tramway system on a certain route in Birmingham has resulted in very serious disturbance to trunk circuits between that town and other towns in the West of England. The engineers of the Corporation have in hand the provision of remedial measures, but inductive effects are causing at the moment considerable inconvenience to the Post Office and to the public.

(*Communicated.*) The author in his verbal reply stated in effect that, as the disturbance had not come under notice until 12 months after the mercury converters were introduced, the interference could not be very serious, although the Post Office cables run close to the tramway track for some distance. It is true that complaints of disturbance were not received until the middle of June of this year, and the more serious complaints on the 1st August. The explanation is that the increases in the trouble were apparently due to extensions of the tramway system along the road on which the Post Office wires are overhead and not in cable, and the accentuation of the disturbance coincided with the opening of a new substation by the Corporation at the beginning of August. Overhead telephone wires are much more likely to be disturbed than those in underground cables, and this, coupled with the working of substations in parallel, no doubt accounts for the late appearance of the trouble.

[The author's reply to this discussion will be found on page 186.]

North Midland Centre, at Leeds, 25 November, 1924

Mr. C. I. Shuttleworth: I am glad that the author stated at the commencement that he had no brief for this system on a periodicity of 50, as I also have not been able to make out a case on this frequency. In the first case the cost is considerably higher than that of any other form of converting plant. I have taken out comparative figures of the relative cost per kW and, for practical purposes, if 250 kW is taken as the standard the costs per kW are approximately £1 for a static transformer, £5·8 for a rotary converter, and £8 for a rectifier. In addition, the static transformer gives no trouble due to back-firing, and possesses none of the other drawbacks inherent to the use of mercury-vapour rectifiers. On a new installation there is absolutely no case (at least I cannot see one) for a mercury-vapour rectifier. There is, however, a case for such apparatus in certain outlying districts where a d.c. supply is already established and the problem of either changing over to alternating current or augmenting the existing supply has to be considered. We in Hull have been looking to the mercury rectifier to get us out of a certain amount of difficulty primarily on account of the noise produced by rotary converting plant. With the development of modern rotary converters and the various forms of automatic gear, I cannot see that there is a case for such a small mercury-vapour rectifier plant except (on the plea of absence of noise) in the residential districts, and for that particular reason we have been considering an experimental substation in similar circumstances to those that have arisen at Birmingham, i.e. the supply to outlying residential areas. In addition to the cost, considerably more ground space is required. In a substation not very much larger than the one shown as containing 600 kW of mercury-arc rectifying plant we are accommodating 2 000 kW of rotating converting plant. I agree with the author that the ideal is to use high-tension distribution as much as possible. I think that substations have in the past been made too large and that too much money has been sunk in copper in the attempt to centralize them. We in Hull have limited our standard substations in the centre of the town to four 500-kW sets. Comparatively small units are put down where they are required to suit local conditions. In ordinary towns, however, the difficulty of getting sites, and various other difficulties, make it impossible to have a considerable number of substations and one is obliged to centralize to a certain extent. Whilst the adoption of mercury-vapour rectifiers on a fairly extensive scale at Birmingham may have met present difficulties, I think that in the future it will be found that the units are too small to cope with the growing load. We have been developing a system of central control that would enable a whole town to be run on unattended substations. We have had a considerable amount of success, and I feel quite sure that within the next few years we shall have a complete centralized control system of supply, all the converting plant being controlled by means of pilot wires from the various substations. This, in my opinion, is superior to a number of automatic substations in which no one knows what is happening. The load can be directed at will by one controlling brain governing the whole of the town area. I do not think that the author would claim that his system is equally suitable for a heavy industrial town load, its special application being for rural areas and primarily for non-standard periodicities. The maintenance costs given in the paper are considerably higher than we have experienced in Hull. Our plant capacity is approximately 30 000 kW; half of this is in rotary converters in various sizes from 250 to 1 000 kW, and the remainder in static transformers. We have approximately 20 rotary-converter substations and 35 static substations and the total charges—including the foremen and all the attendance and cleaning—are about £2 100 per annum, apart from salaries. This is equivalent to £0·07 per kW of plant installed. Our charges are therefore about one-tenth of those indicated in the paper for a rotary-converter substation, and about one-third of the charges for a mercury-vapour rectifier substation. From our point of view, therefore, one of the strongest claims made by the author is not justified. There is no saving in attendance or on capital cost for the plant alone—apart from the feeders. I agree that a considerable saving can be shown on low-tension feeders by putting down smaller substations. The ripples on a supply system raise a very serious difficulty and there is something

to be said for the plain rotary converter which does not give such pronounced ripples as the mercury-vapour rectifier does. With regard to the rectifier generally, it certainly simplifies the automatic control gear, although in the system we have evolved we have no more relays than are required for the rectifier plant. The operating engineer is kept in close contact with the machine through instruments during the whole time the plant is running. He can stop it at any part of the process of running up. He has an indication of the load and the voltage and he can adjust these to suit the prevailing conditions. He can shut the machine down and close or open the low-tension circuit breakers at will. With the exception of not being able to see the machine, he can in fact perform all the functions of a manually operated substation. These developments rather lessen the scope for the mercury-vapour rectifier. With regard to the reliability of rotating plant, we have run unattended stations for over 20 years. During the whole of that time we have lost only two bearings: one due to a fractured sight-glass on the oil pump and the other due to a misjudgment on the part of the attendant as to the height of the oil in the well. These difficulties have been overcome by a different type of bearing which dispenses with sight-glasses and allows the rings to dip further in the oil well. All unattended rotating plant should be fitted with pump lubrication in addition to rings. Our experience proves that the risk of running unattended substations is very little greater than it is with manually operated substations or with mercury rectifiers. It may in fact be less, as it seems to me that eventually when the bulbs get impaired there is certain to be a dead short-circuit. I should be glad if the author would indicate how the regulation would be effected in order to ensure that each unit took its proper share of the load in a substation having an aggregate capacity of, say, 2 000 kW.

Mr. W. A. A. Burgess: The author appears to have made out a good case for the mercury-vapour rectifier for loads up to 250 kW at 25 periods. Beyond that I cannot see any case for the mercury-vapour converter in its present state of development. I am fully in agreement with Mr. Shuttleworth on the question of costs, and in Appendix 2 I do not think that the author is quite fair in his estimate as regards rotary plant. He has installed three 500-kW rotary converters to take the load that is dealt with by four 276-kW rectifiers. Two 500-kW units would apparently have sufficed. If he had made these completely automatic or, cheaper still, if the cost of pilot cable is ignored, made them remote-controlled on the principle successfully adopted by Mr. Shuttleworth, the cost would have been at least £8 000 or so cheaper and somewhere about £1 600 per annum would have been saved. It will be seen from the comparison between estimates (2) and (3) of Appendix 2 that there would then be very little difference, if any, in favour of the mercury-vapour converter. That of course assumed that he was able to obtain three suitable sites and put one 500-kW set on each in order to save a proportion of the low-tension feeder cost as in the case of the mercury-vapour equipment. On the question of buildings I agree with Mr. Shuttleworth. The buildings illustrated are certainly ample for the job, and I should be prepared to put forward an equipment which would provide fully 1 000 kW in two 500-kW sets in one of the 276-kW substations. The roof for rotating plant would have to be higher, and the foundations heavier. I think the estimates for building are unduly liberal. As regards the actual value of the mercury converter, I can foresee a very good future, in spite of its present inherent disadvantages, for stand-by plant in the form of a mobile unit capable of being moved from station to station. As a stand-by for rotating plant it should be an excellent thing. It is a light equipment, it can be easily moved, and transformers could quite well be designed for rotary converters with suitable tappings to supply mercury converters. Further, with the type of control equipment put forward by the firm with which I am associated, the modification of the switchgear and control gear would be extremely small, and such as could be provided for in advance at very little cost. I am rather impressed by the author's remarks regarding the severity of the short-circuit on both types of mercury arc. There seems to be no way of countering this, except on the a.c. side, with complete suppression of the arc and the necessity for restarting. One cannot use the d.c. high-speed reactance form of circuit breaker which has proved so effective in preventing flash-over on rotary plant. This type of circuit breaker definitely limits the short-circuit current to some 7 or 8 times full load and clears within 0·03 sec., compared with the more usual 18 to 20 times full load for a much longer period, and completely saves the brushes and prevents flash-over. The author raises a new point when he mentions the forming period required by the Brown-Boveri type of mercury-arc rectifier; both the preliminary period and the periodical one after being out of service for 24 hours appear to constitute a real drawback. It reminds one of the periodic charging required by the "aluminium arrester" on which so much faith was placed when it was first introduced into this country and in which American engineers apparently still have faith. The charging process with this apparatus was distinctly uncertain and a short-circuit was possible. The author seems to think that there is some risk in adopting totally automatic rotary-converter equipment, but after the risk voluntarily undertaken in the development of mercury arcs I think he need have no fear on that score. It is true that the original completely automatic rotary-converter equipments were rather complex, but I think it will be agreed that the latest types, particularly the type manufactured by Messrs. Reyrolle and demonstrated by them at the British Empire Exhibition, are as simple as anything that could be shown to us; certainly much simpler in arrangement than the panels and equipment shown on the lantern slides exhibited by the author. The complete diagram is no more complex than that of the author's own mercury-vapour equipment, with the exception that some 4 or 5 more relays are required for synchronizing and other purposes. The equipment has been proved in service to be as stable as manually operated plant, and more dependable in emergency. Mr. Shuttleworth's equipment also

tends to prevent operators' mistakes, as the operator only has to manipulate a simple selector device and press a button in his distant control room. I have seen the equipment supplied to Mr. Shuttleworth, although I have not had an opportunity of examining it on the site, and I could see no cause for apprehension. With regard to the author's final remarks on ripples, with rotary converting plant the ripple effect is practically negligible. The author states that the Post Office is already complaining of ripples due to his mercury converters, and I am afraid that his colleagues in charge of fault protection will also be likely to complain of high voltage induced in neighbouring pilot wires. Cases have been known of breakdown of pilot cables due to high voltage induced by external high-frequency currents, and I am of opinion that a heavy d.c. fault on a circuit supplied by mercury-vapour equipment of considerable size will prove to be a parallel case. The figures given in the paper appear to contain no provision for loading the rectifier when the d.c. circuit breaker opens on a fault. I suppose that that is merely an omission, and that there is actually a loading resistance in case all feeder circuit breakers are out at the same time. In such a case it would appear that the arc would be extinguished unless a loading resistance were provided. Again, one of the figures shows a connection to the pressure-lowering equipment from the d.c. shunt. When the load reaches a certain minimum value the circuit breaker opens, but connections are also shown to the pressure-lowering equipment. Apparently at a predetermined excess current the pressure is definitely reduced to a certain value. What is that value, and what would happen when supplying an isolated network? Would there still be such a connection to the pressure-lowering equipment, and, if so, how much would the pressure be reduced before the "low-volt" condition on the network caused a balance between the "raise" and "lower" coils of the controlling relay? If on a network in parallel, the other stations would pick up when the mercury arc lowered the pressure. Nothing would happen if the pressure fell, but unless there is a limit to the pressure-lowering with an isolated system it appears that the maximum-current relay should be left out or at least not connected to the voltage regulator.

Mr. W. H. N. James: Some 20 years ago a distinguished foreign electrical engineer, M. Leblanc,* made the statement that, so far as epoch-making inventions were concerned, the electromagnetic principle was played out and that attention must be paid to the vacuum tube. The accuracy of this prophecy has been largely borne out by the discoveries concerning the vacuum tube which have been made during the intervening period, and by the many commercial applications of this device not only to light-current engineering but also, as this paper shows, to power work. In nearly all d.c. circuits fed from electromagnetic machines, ripples are very noticeable and may arise from the effect of slots, the effect of eccentricity of the rotor and, in an irregular form, from sparking at the commutator. Can the author give some idea of the relative magnitudes of the ripples commonly met with in such circuits and of those commonly met with in circuits supplied from rectifiers? Information concerning the relative magnitudes of the ripples in circuits fed from glass-bulb rectifiers (with three anodes) and in circuits fed from Brown-Boveri rectifiers (with six anodes) would also be of interest. Another point in which I am interested is in connection with parallel running. In the early days of the mercury-arc rectifier I believe it was necessary to have a special balancing transformer on the a.c. side when tubes were run in parallel, presumably on account of the differing characteristics of the several tubes. I should like to know if this precaution is still necessary and also if rectifiers run well in parallel with rotary converters connected to the same d.c. busbars. The process called "forming" is, I understand, a means of getting rid of occluded air rather than any more material change in the surface of the anodes, and I should like to know, in the case of Brown-Boveri rectifiers, if re-formation is necessary after a short period of idleness if the vacuum has been maintained in the interval.

* See *Journal I.E.E.*, 1913, vol. 51, p. 710.

Mr. T. B. Johnson: I should like to ask whether this method has been tried in places other than Birmingham, and, if so, to what extent. The Post Office Telephones Department used small mercury rectifiers to a fairly considerable extent in comparatively small centres, Harrogate for instance, for charging secondary cells. We had a good deal of trouble, owing partly to transformer faults but chiefly to the failure of the mercury-arc rectifier; consequently the maintenance was troublesome and costly. We have replaced them by "Tungar" rectifiers, which are similar in form to the ordinary amplifiers used in wireless work. In that way we have entirely eliminated the troubles. The mercury arc, if it stops, must be started again by someone on the spot. With the bulb any stoppage is merely for the period of the fault, and the bulb comes into use quite automatically as soon as that is overcome. Does the author think that it would be practicable to develop this "Tungar" rectifier in such a way that it would be suitable for electrical stations of the size he has described? I assume that the large saving in first cost, of which the author speaks, in laying high-tension cables with automatic rectifiers at the distant end, as compared with low-tension cables with static transformers at the principal station, is entirely due to the smaller amount of copper used. If so, I should have thought that it would be necessary for the lines to be of considerable length in order to wipe out the large cost of the apparatus at the substation. I should be glad if the author would give us some information on the important point of the extent to which the duration of the faults has been increased by installing these substations.

[The author's reply to this discussion will be found on page 186.]

SOUTH MIDLAND CENTRE AT BIRMINGHAM, 3 DECEMBER, 1924.

Mr. F. Forrest: I suggest that the description of the apparatus referred to in the paper should be "Mercury-Arc Rectifier" and not "Mercury-Vapour Rectifier." The author uses both terms in the paper, and I think that the correct description should be standardized and always used when referring to this particular apparatus. The very brief reference made to the 225-kW Brown-Boveri rectifier which has been in regular service in Birmingham for over 3 years, hardly does justice to a piece of apparatus which has given extremely satisfactory service in connection with both low-tension lighting and traction supplies. The fact that this type of rectifier cannot at present be obtained in small units has militated against its more general adoption in Birmingham. The steel-clad water-cooled rectifier is, in my opinion, a much better type than the glass bulb cooled by an air blast from a fan. The glass-bulb type is not shielded from external magnetic fields, which may deflect the arc and cause internal short-circuiting, whilst the cooling cannot be uniform over the surface of the glass bulb. I believe that certain experiments have been carried out in Germany with the glass-bulb type of rectifier immersed in a steel tank filled with oil. It seems to me that this experiment may give very good results, increase the output and lengthen the life of the bulb. It will lead to more uniform cooling of the bulb, shield it from external magnetic fields and further assist in maintaining the high vacuum required. The descriptions of the protective relays used in connection with the rectifier, rather mask the fact that the control relays required are few in number and simple in the operations they have to perform. In this respect the rectifier has an immense advantage over the automatically controlled rotary converter. I should be glad if the author would state the number of relays normally required for the control of the glass-bulb rectifier, as compared with the number required for the complete control of a rotary converter for the same class of service. The successful use of these rectifiers for developing the outlying parts of the City of Birmingham on the low-tension direct-current system, which, as the author points out, is on the whole the best system from the consumer's point of view, is one further reason why the present methods of generation and distribution of electricity should not be too rigidly standardized, as it is certain that further improvements along the lines described in the paper may substantially alter what is at present regarded as standard practice in most parts of the country.

Mr. R. G. Jakeman: In connection with the automatic voltage regulator, the author uses a regulating transformer with tappings and sliding contacts. Has the question of using an induction regulator been considered, and, if so, how does it compare? Has the author considered the use of condensers on the h.t. side to improve the power factor? Is it necessary to use a high-speed circuit breaker in case of a short-circuit just outside the substation? It is possible to be troubled with telephone interference both with mercury rectifiers and with rotary converters. I have just obtained oscillograms from a large 25-period rotary converter which show that the tooth ripple on open-circuit is so small that it is difficult to read its value, while the sixth-frequency ripple on full load is only about $\pm \frac{1}{2}$ of 1 per cent.

Mr. J. T. H. Legge: The one point on which I find myself in disagreement with the author is his statement in the third paragraph of the introduction to the paper, where he says that a frequency of 25 periods per second is unsatisfactory for domestic purposes, and that it becomes necessary either to convert to direct current or to change the frequency. Within 10 miles of the City of Birmingham are several thousands of houses lighted by electricity at 25 periods per second, and I can safely say that up to the present time not a single complaint has been received as to it being unsatisfactory owing to the low frequency. I should like to remind the author that the entire supply of current from the Niagara Falls stations, on both the American and the Canadian side, amounting to a total plant capacity of 1 000 000 kW, is generated, transmitted and distributed at 25 periods per second. The area covered is many hundreds of square miles, in which is situated the City of Buffalo with over half a million inhabitants, and every lamp is operated at 25 periods per second. I am sure, however, that the field for conversion of alternating current by means of mercury-vapour rectifiers is rapidly widening where such change is necessary.

Mr. C. W. Goodman: Operating engineers, both in this country and abroad, will particularly welcome this paper as it shows in detail how a particular problem was attacked and the results which were obtained. It is not often that a paper such as this gives both the advantages and disadvantages of the method adopted and the comparative costs of alternative schemes in such detail. It is, perhaps, a pity that the question of using frequency-changers and a low-tension 50-period network instead of direct current has not been dealt with more fully in the paper. The reason for this is made more apparent by the author's supplementary remarks. Frequency-changers are reliable machines and very easy to operate, and being installed in a generating station would not require any extra supervision. Sets rated at about 1 500 kVA could be purchased for about £4 per kVA complete with starting gear, and as modern frequency-changers have a good efficiency it would appear that the overall efficiency of the system would be higher than is the case with small rectifier substations, dealt with in the paper. I should like to know whether the author considers that on a system where no commitments had been made in the outer area, this alternative would not be the best to adopt. It would appear from that part of the paper which deals with the steel-cylinder rectifier, that if it is desired to keep a special rectifier standing by, as would be necessary in the case of important traction substations, the set would have to be kept on a light dead load in order to prevent the half-hour delay before it could be put on the line. This seems to be a serious matter, as the stand-by losses would be a big item in a year's run. The ripple present in these

rectifiers is mentioned in the paper. On the higher voltages and frequencies generally met with in railway electrification, the amplitude and frequency of the ripple would be much greater, and one wonders whether the resultant heating on unlaminated magnetic circuits in d.c. apparatus connected to the system would not be serious. Turning now to the question of regulation, it would appear from other published matter on these rectifiers that the voltage characteristic from full load to 1/10th load is comparable with that of other electrical machines. Apparently, however, below 1/10th load the voltage rises considerably and to a very high value on open-circuit. It would be interesting to know how this is dealt with, as one can conceive that should a heavy consumer throw off his load from a substation, leaving only a few lamps in circuit, these might be damaged due to over-voltage. Reference is made in the paper to the important question of the design of substation buildings, and I feel that very often more attention should have been given to this matter on systems where the inhabitants have complained of unsightly substation buildings being situated in better-class residential areas. As the subject of noise has been mentioned, I should like to say, on behalf of the rotary converter, that a good deal can be done in the design of the substation building towards eliminating noise altogether, without excessive increase in cost. In Appendix 3, the cost of the e.h.t. switchgear, consisting of seven 5 000-volt panels, some if not all of which would be electrically operated, is £323, or £46 per panel. On the other hand, in Appendix 2 the figure for e.h.t. switchgear in a manually operated rotary-converter substation where five 5 000-volt panels are required, is £800, or £160 per panel. I should like to know the reason for this discrepancy, as if a more expensive switch is necessary on rotary converters one would assume that it is also necessary for the rectifiers.

Dr. C. C. Garrard: From the psychological point of view I think that the employment of attendants in substations is to be deplored. Generally speaking, they have very little to do, and I am sure that to spend any length of time as a substation attendant must have a very bad effect on young electrical engineers. I, myself, am a believer in automatic working, and am convinced that it will come more and more into use. As the author has shown, a rectifier appears to be ideal for automatic working, and the gear required is certainly simpler than that necessary for automatic rotary converters. As regards the system of electrical distribution to be adopted in the future in this country, I believe that this will remain direct current in the great majority of cases. The author's case is, of course, based upon a 25-period system, where the advantages of d.c. distribution are certainly greater than if the standard frequency of 50 had been adopted, but if distribution is to be by direct current I take it that a good case could be made out on a 50-period system. I should be glad if the author would state what, in his opinion, is the largest size of rectifier which is commercially practicable at the present day, and when he would begin to install automatic or non-automatic rotary converters. The reports available regarding the operation of large rectifiers are certainly very variable. The conclusion I have arrived at is that their reliability is not so great as that of a modern rotary converter. It would, I think, be most valuable if the relative reliability of the largest practicable size of rectifier, compared with that of the corresponding rotary converter, were thoroughly explored.

Mr. R. A. Chattock: When the question of giving a supply to the outlying residential districts of Birmingham had to be considered, the following decisions were arrived at. An a.c. supply at 25 periods per sec. was considered to be unsuitable, owing to the slight flicker that is noticeable. The proposal to install frequency-changers to change the frequency from 25 periods to 50 periods and to supply the districts with 50-period alternating current was carefully gone into and compared with the proposal to use rectifying plant and to distribute direct current on a three-wire network. The drawbacks to the frequency-changer scheme, which was admittedly cheaper than the rectifier scheme, were: (1) a much lower efficiency of transformation; (2) the impossibility of linking up the distributing networks with the existing d.c. networks in the city, which are all provided with a battery stand-by; (3) the greater suitability of direct current for heating, cooking and the small power apparatus used in private houses; and (4) the less risk of shock with direct current compared with alternating current. The Birmingham undertaking had already obtained experience with a Brown-Boveri steel-cylinder rectifier, which had been in use at one of the substations running by itself, and also in parallel with rotary converters and a storage battery. The excellent results obtained with this piece of apparatus prompted a very careful inquiry into the use of the glass-bulb rectifiers which, it was felt, were more suitable for small power substations which it was proposed to install for feeding into d.c. networks, with a view to eliminating the heavy cost of long low-tension feeder mains, and manually operated rotary-converter substations. As a result of these inquiries it was decided to adopt the glass-bulb rectifier plant, and it is gratifying to know that these have proved to be highly satisfactory. Their use has been extended also for tramway traction purposes. For substations of larger capacity it will probably be found that the automatic rotary converter is more suitable, but in residential districts the rectifier is preferable on account of the greater simplicity of the automatic controls, and also because of the silence with which it runs, the latter being particularly important in a residential district. The experience in Birmingham with these glass bulbs has been highly satisfactory. Not a single failure of a 230-volt bulb has occurred, and there have been very few failures on the higher voltages. It is a very simple matter to take out a bulb and replace it if it does happen to fail. It should be remembered that apparatus of this kind is of fairly recent development for capacities of 25 to 100 kW, and that in all new apparatus a certain amount of pioneering work must be done and experience obtained before the various little difficulties that always arise can be overcome. The question of interference with telephone circuits, owing to the high-frequency ripple in the direct current supplied from these rectifiers, has been mentioned. So far, we have only had one complaint of this effect on the traction route that has been referred to in the paper, where the currents are fairly heavy and the overhead trolley wire

is of course at a distance from the return rail. Continental experience indicates that the insertion of a resonant shunt in the circuit will completely remove this trouble, and this apparatus is now being installed. As regards the Brown-Boveri steel-cylinder rectifier, this has also given us entire satisfaction as regards its operation. At the present time, however, the apparatus is more expensive than the automatic rotary converter, which for larger sizes is quite suitable. It is also manufactured abroad, a fact which, under present conditions, rules it out so far as Birmingham is concerned.

Mr. A. E. Angold: I should be glad if the author would give some information on the following points:

(1) The cost of upkeep (per kW output) of a rotary converter, compared with that of motors for cooling fans and voltage regulators used with Hewittic rectifiers.

(2) Does a rotary converter need (per kW output) any more "minding" than the fan motors and voltage regulators mentioned above?

(3) Which creates the more noise (per kW output)—the rotary converter or the above-mentioned fans?

(4) What is the percentage voltage ripple between outers and middle wire with 3-anode and with 6-anode rectifiers, and what would be the extra cost of effective chokers in the middle wire and voltage regulators supplied to each side of the middle wire in connection with 3-anode rectifiers?

(5) What are the percentage extra costs of transformers and the percentage extra loss in the same for 6-anode and for 3-anode rectifiers, as compared with rotary-converter transformers of equal capacity?

[The author's reply to this discussion will be found on page 186.]

Mersey and North Wales (Liverpool) Centre, at Liverpool, 15 December, 1924.

Mr. P. J. Robinson: The author has produced a d.c. distribution from a 25-period supply, and, whilst appreciating that his difficulties are very real, I cannot agree with some of the statements which he makes when trying to justify his particular method. He states that direct current has distinct advantages over alternating current for the supply of the domestic and cooking load. If he is referring to a 25-period supply I am bound to agree with him, but if the supply is at 50 periods I wholly disagree. Some hundreds of houses in Liverpool are supplied with alternating current, and of the two, from the point of view of distribution and supply, I prefer alternating current. We find it is far more flexible. I admit that the direct-current supply has an advantage in power work in regard to speed regulation, but this disadvantage has to a large extent been overcome by means of cascade motors, by pole-changing and by commutating a.c. motors where wide variation of speed has been called for. This slight disadvantage is, in my opinion, far outweighed by the advantage of the flexibility of the a.c. distribution. With regard to the general power supply, I do not think that the author has put forward any case which justifies the use of rectifiers. With regard to automatic stations, I agree with the author that these have their use, not for feeding long and lightly loaded distributors, but for the purpose of maintaining the pressure in congested areas over periods of peak load. It would not be advisable to deal with a new district by means of a low-tension d.c. distribution, an efficient a.c. distribution being far preferable, and I think that the author adopted the present system more by force of circumstances than because he is strongly in favour of it. We, in Liverpool, have had some experience with fully automatic stations, and during the time that they have been in operation (one has been working since August 1922, and another since September 1923) there have only been two mishaps that might be called breakdowns; in both these cases the supply was not interfered with but the automatic station refused to operate. On the first occasion the trouble was due to a flaw in the metal of the brush-raising gear, and in the second case to a pilot brush sticking in the holder. The author states in col. 2 of page 165: "The method of starting up and shutting down the set as required is comparatively simple, and follows the practice adopted for automatic rotary converters. It is, however, much simpler and requires a smaller number of relays." I have carefully studied the author's Fig. 11, and, comparing the number of relays and fuses with that of an automatic rotary station, I find that there is little to choose between them. In fact the automatic station with the same amount of protection has actually fewer relays, but in the case of the automatic station put forward in my paper * the safety of supply and plant is looked after in a far more efficient way than in the station put forward by the author, so that the actual comparative number of relays depends largely on the care taken in giving the supply. The author states that the life of a bulb is very long. I do not consider that 8 000 hours (which is less than a year) is a very long life for any piece of electrical apparatus, and I would suggest that where he is opening up d.c. distribution in new districts, i.e. where he is using two bulbs across a three-wire 460-volt supply, the consumers would be subjected to a periodic shut-down, more especially if the substation in question were not coupled up to its neighbour. It would also appear that when supplying consumers from two bulbs in series on a three-wire system, the middle wire, or neutral, would have to be of the same section as either of the others.

Mr. T. W. Ross: The steel-cylinder or Brown-Boveri type of rectifier is, for several reasons, not very well adapted to automatic control, and the author states that one of the drawbacks is that the anodes have to be re-formed after each shut-down of 24 hours' duration. This seems to be a decided disadvantage as, although the forming operation can be done in 30 minutes, it seems desirable to be quite sure that it has been successfully performed before switching on. The main trouble, however, is the vacuum in the

* "The Maintenance of Voltage on a D.C. Distribution System by Means of a Fully Automatic Substation," *Journal I.E.E.*, 1923, vol. 61, p. 417.

cylinders. For successful operation this must be maintained to the extent of somewhere about 0·1 mm of mercury. In looking into the question of automatic control for these rectifiers some two or three years ago, I found that the measurement of the vacuum was a most difficult matter when, in addition to measuring the vacuum, it is necessary to operate a contact device to initiate the operation of the automatic switching apparatus. The vacuum gauge supplied with this rectifier has to be operated by hand in order to obtain a suitable scale reading. It seems to me, therefore, that unless the author has some suitable means of automatically measuring the vacuum and initiating switching sequence at the correct moment, there is a grave possibility of short-circuits or flash-overs taking place. I note that it is not necessary to run the exhaust pump unless the load is greater than 50 per cent, but this will no doubt mean running the pump all the time, as one can never be sure what load may be demanded from the rectifier. This also means that the vacuum-measuring device must be in service all the time the rectifier is on load, and ready to shut it down if and when the vacuum fails. Referring to Fig. 1, I notice that there are no fuses between the transformers and the rectifier. Are fuses no longer used? The last time that I examined a rectifier equipment, each anode circuit was carefully fused. I suppose that these fuses are to take care of the heavy short-circuits which can take place if the vacuum fails, or for any other reason. The glass-bulb type of rectifier is much more suitable for automatic control and offers very little difficulty in that direction. The greatest drawback to this type of rectifier seems to be the comparatively small size of the converting unit and the delicate nature of the glass bulbs. The question of simplicity of the automatic control gear is very often raised by operating engineers and is a point which at times is very much over-stressed. To say that the control gear for these glass bulbs is more simple than that for an automatic rotary converter is to my mind of very little importance from an operating point of view. The manufacturing undertaking that sells automatic substation control gear has to provide such protective apparatus as will give protection to the converting plant under all conditions and, moreover, must discriminate between faults inside and outside the substation building, so that the converter will not be locked out of service unless absolutely necessary. That is where most of the so-called complication comes in and gives rise to the necessity for most of the relays used. The actual control gear for an automatic rotary converter is very simple and, in comparing the two schemes, this fact must not be lost sight of. In any automatic control scheme a certain amount of development is very often brought about by the process of evolution, and I believe that the author will find, if he has not already found, that certain additions to the control apparatus are desirable in order that certain conditions may be taken care of. For instance, I see no means of disconnecting the bulb if the cooling fan fails, and I presume that it will be necessary to do this as a safeguard against damage to the bulbs. In comparing the cost of a converting plant with rotary converters against that of rectifiers, I think that it is only fair to take into account the overload capacity of the two equipments, and I should be glad if the author would give the overload capacity of the two types of rectifiers mentioned. The manufacturer of rotary converting machinery is continually being asked to increase his overload guarantees, and one must not overlook this fact when the rating of the plant is considered. It is also very difficult to compare the cost of switchgear. The breaking capacity of oil switches, the number and type of auxiliary apparatus used, etc., all give room for considerable difference without affecting the actual switching operations. If, therefore, we compare the cost of an automatic rotary converter equipment with that of an automatic rectifier equipment, it would be more accurate to leave out any switchgear or control gear common to both. Taking the figures given by the author in Appendixes 2 and 3, I find that without this common switchgear the prices of automatic rotary converters will compare very favourably with those of rectifiers, showing a decided balance in favour of rotary converters. The cost of the d.c. switchgear given in Appendix 3 seems very low, as apparently this includes five automatic reclosing circuit breakers, knife switches, meters, slate panels, angle iron, copper busbars and connections, and all auxiliary apparatus. I feel that some mistake has been made here and I should be glad if the author would state exactly what gear is included in this price. No mention is made in the paper of the limitation of the mercury-arc rectifier station and I am sure that there must be some point where it is desirable to install rotary converters instead of rectifiers. This is more or less proved by the fact that the Birmingham Corporation sometimes order rotary converters, and it would be interesting to know under what conditions these are found to be more suitable than mercury rectifiers. In conclusion, I think that the schemes outlined by the author are probably more suitable to the particular conditions existing at Birmingham than to the general problem of converting plant.

Mr. J. H. Williams: The author gives the cost of the rotary converters on page 172 as £6 per kW, and of the rectifiers as £8, therefore it would seem that the difference in cost is mainly due to the type of switchgear used. In the case of rotary converter installations already running, practically the maximum number of protective relays have been put in, whereas the Birmingham Corporation, who have themselves provided the switchgear, have approached the problem with the idea of having the minimum number of relays, a frame of mind not usually found in purchasers. The efficiency of the mercury rectifier on 230 volts is low; also it seems questionable whether it would not pay to put in a 300–500 kW rotary converter at the start rather than put in a 46-kW mercury rectifier and then have to keep adding to it as the load grows. The mercury rectifier cannot claim to take up less space than the rotary converter. I should like to know whether the author is prepared to give the cost of the bulbs, and also the average life; both of these items would be of interest. I gathered from the author's opening remarks that the overload capacity of the bulbs is limited to something like 4 to 5 per cent.

Mr. L. Breach: On one lantern slide exhibited by the author there appear to be some oil circuit breakers controlling the d.c. supply. I should like to know whether any trouble has been experienced with these switches and whether the carbonization which takes place on opening circuit has had any ill effects. Has frequency any effect on a flash-over, that is to say, is the risk greater or less at 50 periods than at 25 periods? Speaking of telephonic disturbances, the author appeared to be rather anxious about the results that he would obtain from the insertion of reaction and resonant shunts, but I can assure him that if he has taken the same values as we have in Liverpool his troubles with the Post Office will cease, as we have been fortunate in eliminating all disturbances. I should be glad if the author would say whether any loading resistance is left across his rectifier when operating on a traction load; this would appear necessary, otherwise the bulbs will require tilting each time the load on the line drops to zero. Also, has he found the reclose breaker satisfactory on traction, and is there a limit to the number of times it operates? It seems to be a dangerous proceeding to leave a breaker to close as soon as the fault is removed, as it is of course equivalent to clearing a fault with pressure on. Referring to the designs of substations adopted by the author, I should like to describe the method by which we have solved the question of ventilation in Liverpool. In all cases we introduce cold air into sealed ducts under the transformers. Through the floor under each transformer is a 12 in. pipe, and as there is no other inlet into the substation all cold air must pass round the transformer and out through a large ventilator in the roof. The inlet ventilator is above ground-level outside, with a duct built into the wall and into the transformer air-duct. We have found this cheap to construct and the results have been most satisfactory, all short-circuiting of air having been done away with. In Figs. 4 and 5 there appears to be one transformer for four rectifiers, and in Fig. 5 there is apparently no switchgear between the transformers and the rectifiers. Apparently if one rectifier develops a fault the only protection is the oil switch controlling the transformer, and if this operates all four rectifiers will be shut down. It is, of course, possible that some switchgear is inadvertently left out of the figure.

[The author's reply to this discussion will be found on page 186.]

North-Western Centre, at Manchester, 16 December, 1924.

Mr. H. A. Ratcliff: It is evident that the choice of a direct-current system of suburban distribution has been influenced by the comparatively low frequency of the Birmingham high-tension alternating-current supply system, and to that extent it is perhaps permissible to say that the author is making a virtue of necessity, since he admits the conveniences and advantages of a three-phase, four-wire distribution network—provided that the frequency is suitable for a lighting load. The occasion is not opportune for a discussion of the relative merits of a.c. versus d.c. systems of distribution, but it is significant that the author refers to the advantages of direct current for domestic loads, and as there are still a few advantages attaching to a d.c. system of distribution it would be helpful if he would amplify his reference to the domestic load. Assuming that the only cure for a low a.c. frequency is a d.c. system of distribution, the case appears to become largely one of substations versus feeders, and undoubtedly, within reasonable limits, a gradual increase in the number of substations is the correct policy—it is, in fact, the policy which is being carried out in Manchester, although not quite on the extensive scale advocated by the author. It follows as a natural corollary that small substations must be either fully or semi-automatically controlled, if they are to be commercially successful. Manual control is, of course, quite out of the question, even in the case of substations of much larger capacity than those described in the paper. Without a more intimate knowledge of the Birmingham conditions, it is not possible to criticize either the schemes referred to by the author or the figures relating to costs which are given in the appendixes. Substations having a total capacity of only 230 to 276 kW appear to be unduly restricted and, moreover, it is not evident whether these capacities include any margin of spare plant. Experience has shown that such small plant capacities are of very little use for dealing with the rapidly growing domestic heating and cooking loads. Such very small substations are only justified when they are connected directly to the distributing network without any feeders at all, and, as soon as feeders become necessary, the stations are approaching a size for which rotary converting machinery would be more satisfactory and probably more efficient. In one of the appendixes a comparison is made between feeders and 276-kW rectifier substations, but, provided that it is not unduly long, a 1 sq. in. 460-volt feeder has a much greater capacity than 276 kW. There are one or two real advantages attaching to the use of feeders of moderate length. The loan period for feeders is very much longer than that for plant of the same equivalent capacity, and consequently the capital charges are correspondingly lower. Suitably disposed feeders enable the total load capacity of a substation to be increased, with the result that the cost per kW of plant and the proportionate operating costs are both very appreciably reduced. The maintenance of feeders is an almost negligible item and, in the case of new districts, provision can be made for them when laying the distributors. A much more uniform distribution of the pressures, and balance of the load, on a three-wire network are possible when feeders are employed, and the location and isolation of network faults is greatly simplified. The author appears to have experienced very little trouble in obtaining suitable sites for substations; that is very fortunate, because it is essential that small stations connected directly to the network should be located within the confines of a fairly restricted area. In some districts it is extremely difficult to obtain suitable sites, and land-

owners frequently object and even refuse to sell land for the erection of substations. It is possible, however, that the prejudice against substations would largely disappear if they conformed more closely with the architectural amenities of the district, and, therefore, I quite agree with the author that they should be designed by architects. Taking everything into consideration, rectifiers appear to furnish the only means suitable for carrying out the schemes referred to in the paper. The cost of automatically controlled rotary machinery for such small sizes is quite prohibitive. There is, however, some prospect for the employment of small self-automatically controlled machines, particularly in view of the unduly high cost of rectifiers. The author is to be congratulated upon his very effective and comparatively simple automatic control arrangements. Unfortunately, it is a common mistake to make automatic equipments far too complicated. The manufacturers of automatic control gear appear to have a poor opinion of the plant which the gear is to control, and consequently they introduce a variety of devices to meet more or less imaginary troubles. Such a multiplicity of protective devices is quite unnecessary, and the ultimate development of successful automatic gear will be along the lines of gradual elimination of all unessential features. It is an inherent advantage of mercury rectifying plant that it lends itself more or less to simple methods of control, since the rectifiers are non-reversible and there are no synchronizing difficulties. The voltage-control scheme illustrated in Fig. 8 is very ingenious and, so far as can be judged from the description, it should be quite free of any tendency to hunt. One very interesting point is the critical nature of the first few days' life of the bulbs, and therefore presumably the manufacturers allow a reasonable proving period, during which they accept full responsibility for the satisfactory behaviour of the bulbs. In estimating the ultimate life of the bulbs, however, some allowance for possible accidents appears to be desirable, since the residual value of a broken bulb must be very small, if not entirely negligible. The outstanding advantage of the glass-bulb type of rectifier for use in residential districts, and possibly also for boosting purposes in the centres of large cities, is the complete absence of noise. Another advantage is the division of the load between several bulbs, since in the event of one bulb breaking there is every prospect that the load will be carried on the remaining bulbs. Rectifiers of this type should also be very suitable for relieving the load on feeders and distributors in large cities where the cost of additional feeders is very heavy and where it is frequently very difficult, if not impossible, to find room for them, owing to the congested condition of the ground under the streets.

Mr. D. S. Paxton: The reason why in the author's case it is necessary to run the vacuum pump continuously when operating the rectifier at more than half-load, as I understand is the case, is probably the fact that the load conditions are such that the rectifier has never run continuously on full load for any length of time, so that the cylinder has not been fully formed. The final forming of the cylinder is not attained until a number of full-load runs of some duration have been made. In the ordinary way it is found that the rectifiers when fully formed will run on full load without the vacuum pump just as well as they will on partial load. The author has referred to the reduction in the time required for forming. The process has been rather altered since the rectifier was installed in his case, so that a great deal of time is saved. The necessity for re-forming after a plant has been shut down is also entirely overcome, and the rectifier can be put on full load however long it has been standing, provided the vacuum is right. Provision has been made that the vacuum shall always be kept up to the correct figure by the latest type of constantly indicating vacuum gauge, which can be arranged to control the vacuum pump automatically, even if the rectifier is out of service. In such cases if the vacuum drops, the pump can be arranged to start up from an auxiliary supply and thus bring the vacuum back to the correct value, so that the rectifier is always ready to take up its load. The author assumes that the frequency of the ripples in the d.c. supply is six times the fundamental frequency, which is, of course, correct where there is a six-phase connection, but in the three-wire diagram (Fig. 5), showing a first instalment of plant in a small lighting substation, apparently there is one bulb only on each side of the system, to each of which only three phases of the six-phase transformer are connected, so that presumably the ripple in this case will be three times the fundamental frequency of 25 periods per sec., viz. 75. When extensions are made, however, the phase connections to the new bulbs will doubtless be arranged in the reverse manner so that there will be a six-phase connection on each side of the three-wire system. I am not quite clear about the exact arrangement of the special regulating transformer, but I presume that it is on the low-pressure side between the six-phase winding and the bulbs, unless the main transformer itself is tapped and brought out to the regulating switch. I should be glad if the author would give some further explanation on this point. Tappings are not very desirable on a six-phase transformer winding. With three or four tappings per phase there are a large number of connections to bring out, and this is to be avoided if possible. In the comparative estimates of three alternative schemes for dealing with the conditions that arise in Birmingham, I see that in No. (2)—a manually operated substation with low-tension feeders—the allowance for the maintenance of plant is £150, and in alternative No. (3) the same allowance is made for the maintenance of bulbs and plant. I should like to know whether this is purely an estimated figure or whether it is based on any definite tests. In the case of a scheme of this size—four substation buildings each containing a 276-kW rectifier equipment—it appears to me that, to come within this figure of £150, one must assume the life of a bulb to be five or six years. Has this period been definitely taken as a basis?

Mr. A. E. Clarke: I should be glad if the author would say (1) what is the recorded number of shutdowns in twelve months for the best installation of which he has had experience, and (2) what the figure is for the worst installation. Given these two extreme conditions, we shall be able to form some idea of the

relative reliability of this form of conversion. The author mentions that short-circuits are very severe. What does he mean by that? Is it that the bulb is shattered and the mercury distributed over the contents of the cubicle, or is it that the bulb remains intact but the rush of current is so severe as to tax the breakers or fuses installed in circuit therewith? I should also like to know the average life of the high- and low-voltage bulbs under actual working conditions; also whether any warning is afforded before a short-circuit occurs, so as to give an opportunity of changing the bulb before trouble eventuates. The author states that his substations have a capacity of 92 kW, and that provision is made to increase this to 230 kW. Do these substations supply a calculated unit area and, if so, what is that area, or what is the average number of domestic consumers served per substation? On page 161 the author states that the substations are connected to ring mains by means of non-automatic oil switches. It would appear to be questionable practice to link them thus solidly, owing to the danger of shutting down large areas—and so losing one of the greatest advantages of small substations supplying small areas—by trouble which might occur either on any part of the ring main or in any substation. In Fig. 8 the author shows four rectifiers and says that "the supply to the motor is so interlocked with the excitation relay (8) of each rectifier bulb that a failure of a.c. pressure or a failure of any one bulb opens the motor circuit." The correctness of the procedure outlined in the last alternative seems debatable. Assuming that all the rectifiers were carrying 2/3rds full load and one failed, then the other three would presumably take up each 8/9ths of their respective full loads, with the result that the voltage on the line would immediately fall and, in the absence of automatic regulation, would remain low. Thus, just when regulation is most required, it is absent. I should be glad if the author would say whether there is some reason for this. I am rather in doubt whether the mercury-arc method of rectification would ever have been adopted had not the periodicity of the Birmingham supply been the inconvenient one of 25, and in this connection it is interesting to compare the cost of this method with that of changing over from direct current to three-wire single-phase at 50 periods. Recently such a change-over has been effected in this district, the transmission being at 6 600 volts, three-phase, the transformation being effected by means of Scott-connected transformers, each transformer giving a supply to a three-wire system at 460 volts between outers and 230 to neutral. Satisfactory arrangements were made to effect adequate balancing of the transformers. The eventual capacity of the substation is 900 kVA, and the present capacity 300 kVA. The building costs per kVA were approximately the same as those quoted in the paper. The total cost with the present plant (300 kVA) including low-tension gear and connections thereto was nearly £3 000. The capacity of the substation can be increased to 900 kVA for an additional expenditure of £1 200, making a total for 900 kVA of £4 200 and demonstrating that this is a very much cheaper method of effecting distribution than that carried out by the author. Needless to say, the efficiencies and regulation we obtain are better than the mercury-arc method can show, and further, as the distribution system consists of old vulcanized-bitumen mains laid solid, there has been a gratifying diminution in the number of faults which have developed since the change-over to alternating current was effected.

Mr. R. Townend: In considering the glass-bulb type of rectifier, the actual bulbs would appear to be the only parts of the equipment liable to give trouble, and it would be useful to know the approximate cost of a bulb and also its average life, based on the total bulb failures experienced by the author. Also, if a bulb should fail due to any cause excepting mechanical damage, is it possible to have it repaired, or is a new bulb necessary? In comparing the glass-bulb and steel-cylinder types of rectifier, it would appear that the former is more suitable for small outputs. In view of this it would be interesting to know why this type was adopted for the traction substations having the comparatively large output of 660 kW. Has the author any information as to the advantages of air-cooling the bulbs, as compared with immersing them in a tank of oil, which latter method would appear to be simple and effective? In comparing the estimated costs of alternatives (2) and (3) in Appendix 2, it should be noted that the total capacity in alternative (2) is 1 500 kW, as against 1 104 kW in the case of alternative (3).

Mr. W. J. Medlyn: There is one point in connection with the paper which I think is of general interest, and that is the liability of the mercury-arc rectifier to cause disturbances in neighbouring telephone lines, when it is used in connection with ordinary electricity supply purposes. The author touched but lightly on that point when he was referring to current ripples in his description of one of the figures. Fortunately, it is possible to overcome this difficulty, and the method of doing so was described by Prof. Marchant in the appendix to Mr. Bartholomew's recent paper.* I trust that electricity supply undertakers will bear this point in mind if they decide to introduce the system recommended by the author, and plan their arrangements accordingly. Our experience is that supply undertakers are ready to co-operate with us in meeting the difficulties which we know are bound to arise from time to time. This spirit is, of course, as it should be where great public services are concerned. In the matter of electrical design, however, I think that prevention is better than cure, and in the long run it is less costly to all the parties who may be affected. Mr. Ratcliff, in his remarks, rather deprecated meeting trouble half way, but I think that this is perhaps a case where we might make an exception, as we know the trouble is already there.

Mr. G. F. Sills: With reference to the question of prices, in Appendix 3 £5 692 is given as the cost of a 660-kVA rectifier plant. An automatic rotary substation would, however, not cost more—in fact not as much. I should like to suggest that when referring to the rectifier type of plant it should not be called a "static" piece of machinery. I believe I am right in stating that in some types of rectifier plants there are six pieces of rotating machinery, and it was claimed

* *Journal I.E.E.*, 1924, vol. 62, p. 817.

that this particular rectifier plant was a piece of static machinery. Surely a rectifier plant with all these rotating auxiliaries is more likely to break down than a rotary converter plant. With reference to Mr. Medlyn's remarks regarding telephonic interference, it it interesting to note that rotary converters can now be obtained to meet the requirements of the Post Office in this respect.

Mr. G. G. L. Preece: I presume that those who were responsible for installing the 25-period supply in Birmingham were afraid that they could not get rotating converting machinery good enough for a 50-period supply. They did not look far and were of little faith. There *were* good types available even then, I think. It is evident from the paper that the present staff at Birmingham are bolder spirits and they deserve success of their pioneering enterprise. Although I am particularly interested in rotating converting plant I am bound to say that there appears to be a distinct field for mercury-arc rectifiers in certain conditions, and the author has by his enterprise proved that such conditions exist at Birmingham. I do not think, however, that makers of rotating converting machinery need feel any apprehension, as it appears to me that the conditions are at the moment limited to such conditions as exist at Birmingham. The steel type of rectifier has yet to prove itself thoroughly, at all events in this country. I do not know, of course, how far the author will go as to the size of the substations which he will equip with these mercury rectifiers, but if the load grows I rather think that when it gets over 500 kW he will find it necessary to consider installing rotary converter plant and use these mercury rectifiers for other districts where the load is small. In common with Mr. Clarke, I am rather interested as to the result of a short-circuit with this type of apparatus. Has it any bad effect on the mains?

Mr. H. Wilkinson: I should like to give a few particulars relating to the installation of mercury rectifier plant of the Hewittic type for the purpose of boosting up a rather outlying section of d.c. three-wire network. The rectifier consisted of two bulbs in series across the outers and was switched in and out daily by means of a time-switch control on the solenoid-operated e.h.t. switch cubicle. The automatic voltage regulator mentioned in the paper was used to maintain a constant voltage at the substation. The experiment proved highly successful in this instance and the operation of the plant generally was found to be extremely flexible, with comparatively wide e.h.t. and l.t. voltage variations.

Mr. G. A. Cheetham: This paper is another proof of the fact that automatic control has passed through the experimental stage and is now quite a reliable method. Those of us who have imagination have long expected that conversion and even generation would be carried out by some means with static apparatus. I think that the mercury-arc rectifier is a step in the direction which we all expect to be taken in the future. Both automatic rotary converters and automatic rectifiers are established as successful engineering propositions, and it is necessary, therefore, to compare them commercially. In comparing various methods of automatic operation, it is very necessary to consider how many possible contingencies have been provided for. Many supply engineers—for example, Mr. Ratcliff—appear to wish to take some risks, and if they prefer to take those risks it is obviously easy to cheapen the gear. For example, many supply engineers do not consider the automatic protection of bearings to be necessary. They consider that, from their experience, it is quite a legitimate risk to take, but most manufacturers when tendering for apparatus of this kind prefer, for obvious reasons, to cover all the contingencies which in their experience have arisen, even though they may be remote. Supply engineers who are considering and comparing quotations and prices must take these facts into account; if they are willing to take some risk the manufacturers are equally willing to cut out these devices and so cheapen the apparatus. As an example, the author appears to consider it unnecessary to provide for the failure of cooling water or for the failure of the vacuum pump, and it is probably quite the correct thing to do; but some supply engineers would not take that risk, and their gear would be more expensive. For an output of 100 kW the rectifier substation would, I think, be possibly a cheaper proposition, but beyond that output I think that the author's own figures prove otherwise. If the high-tension gear and the d.c. switchgear are assumed to be the same for an automatic rotary converter as for a mercury rectifier, then we can compare them on the same basis; and if we do so an automatic rotary-converter equipment, as suggested in scheme (2), would be £700 cheaper, and scheme (3), with automatic rotary equipment, would be 15 per cent cheaper. The cost of maintenance—£150 a year—seems to be very high and, I think, would not be regarded by an engineer with rotary equipment as anything like a reasonable figure. I expected to find some saving in space with the rectifier equipment, but apparently there is no advantage in that respect. I should like to ask the author whether when the bulbs are maintained continuously on full load he experiences much trouble due to flash-over. One other small point—though to some supply authorities it is very important—is that the advantage of power factor correction cannot be obtained with mercury rectifiers.

Mr. A. Manighetti: Regarding the question of flash-overs, I would point out that these troubles have occurred only in the case of the high-voltage bulbs. It has taken some time to obtain sufficient data as to the conditions under which these bulbs have to operate. The flash-over occurs when the vapour tension has passed a critical point, which point is determined by the cooling of the bulb. This bulb vapour tension or internal pressure is dependent on the cathode temperature, and it is a simple matter to cool a bulb sufficiently to enable it to give its maximum output at a point well below that of the critical vapour tension. It should be remembered that manufacturers of the rotary type of plant have had many years in which to perfect their gear, and in the comparatively short time the mercury-vapour rectifier has been supplied for heavy duties it has been found wanting in only small matters which are easily remedied.

Mr. H. C. Lamb: The author is in the fortunate position of having experience of both the Brown-Boveri

and Hewittic mercury-arc rectifiers, and it would be of interest if he could give some information about the advantages and disadvantages of each type. Referring to the last page of the paper, why is it necessary to provide 50 per cent spare plant for the rotary substation and no spare for the rectifier substation? Does that really represent the relative reliability of the two types of plant? If spare plant were necessary for a rectifier substation the figures of cost would be very different from what they are. Why is high-tension switchgear so cheap for rectifiers and so comparatively dear for rotary converters?

The Author's Reply to the Discussions at London, Leeds, Birmingham, Liverpool and Manchester.

Mr. G. Rogers (*in reply*): Many points have been raised at nearly every Centre, and I propose to deal with these first.

Many speakers have drawn attention to Appendix 2 (2), pointing out that allowance has been made for three 500-kW rotary converters, whereas in the alternative scheme outlined in Appendix 2 (3) only four 276-kW units are provided. To make this matter quite clear, it is necessary to point out that the problem involved feeding into the existing networks at four points. The existing networks at these points were fed from three distinct sources of supply, and could not be linked together. With a new substation, therefore, it would be necessary for the four new feeders supplied from this station to pick up entirely distinct networks and to be linked through to the existing network at one point only, i.e. to only one of the existing sources of supply. Obviously, therefore, it was necessary to have spare plant in the station, as the load to be picked up was over 1 000 kW. By having four distinct and separate substations close to the network, as suggested in the alternative scheme, each unit would start up automatically and feed into the network, and take its full load when required. If a short failure occurred at any time, it would only involve a drop in pressure. Further, it was not practicable to supply the larger station with three 500-kW rotary converters from an existing ring-main feeder, and the proposal involved the laying of new high-tension feeders to the station from the nearest generating station, whereas in the alternative scheme a ring-main feeder in each case was in close proximity to the site of the small substation and simply had to be looped in.

Another point raised by many speakers is the low cost of the high-tension switchgear for the small rectifier substations, as compared with the cost for the rotary substation. For the small substations no instruments of any sort were required on the high-tension side, whereas for the rotary converters it is obvious that many instruments and much gear would be required. Further, the larger units with the new high-tension feeders would involve switchgear of greater capacity than the small units supplied from the existing ring mains.

Mr. Bartholomew and others raise the question of interference with Post Office telephones due to induction caused by the ripples. I admit that in one particular case where the traction supply from the rectifier substations runs parallel with the Post Office trunk lines, some interference is being caused. Steps are being taken to obviate this by installing suitable inductances and resonant shunts in each of the substations to eliminate the ripples causing the trouble. This apparatus has now been tried out in one substation and found to be quite satisfactory. I have no doubt that as soon as we can install the complete apparatus the interference will be entirely eliminated.

Another point mentioned at many Centres is that justice has not been done in the paper to the steel-cylinder rectifier made by the Brown-Boveri Co. The reason this rectifier was not dealt with at greater length in the paper was that full technical details have already been published at various times in the technical Press. Mr. Chattock points out that our experience of this type of rectifier is quite satisfactory, but its high cost has prevented its more general use. A further objection is that the apparatus is made abroad. I feel certain that there is a good future for the Brown-Boveri rectifier for converting to direct current, particularly for traction work at high voltages. In situations where the absence of noise is a big factor, there can be no question that the large unit rectifier can and will be used for converting to direct current.

Corrections have been made in the paper with reference to the "forming" which up to the present has been necessary on the set in Birmingham, and also in respect of the large units that can now be supplied by the Brown-Boveri Co.

Many speakers raise the question of the high cost of the small three-wire rectifier substations, and compare it with that of simple static transformer substations. Assuming, however, that a satisfactory case has been made out for a d.c. supply instead of an a.c. supply, then such comparisons should obviously be made between different methods of conversion to direct current. The rectifier will certainly have the advantage over other plant for the small units. Above capacities of 500 kW it would probably be cheaper to install automatic rotary converters. The cost of the buildings, however, would be considerably more if this were done.

Captain Donaldson points out that the cost of the small rectifier substation works out at approximately £20 per kW, whereas a small static transformer substation of about the same capacity would work out at about £4 per kW. On any large distribution scheme, however, such as the one described in the paper, I would point out that the cost of the substations, whether a.c. or d.c., forms only a small part of the total cost of such a scheme, the greater part being absorbed in the distribution mains. I agree with Captain Donaldson that the overload capacity of a static transformer substation is more than that of the mercury-arc rectifier substation. The explanation of the low efficiency of the three-wire lighting unit, namely 85 per cent, is due of course to the two sets being in series, but

this efficiency compares favourably with the overall efficiency of a small rotary-converter substation with a battery.

All the efficiency figures given in the paper were obtained experimentally, the meters used being indicating instruments. In one particular case, integrating meters were also installed for the test, and it was found that both sets of instruments gave practically the same results. The only error that could creep in would be in the current transformers used in the primary circuit, and it is possible that the distortion in the wave-shape might, to a slight extent, affect the readings obtained from them.

The voltage-regulating device described consists simply of a regulating transformer in series with the main transformer secondary windings, with tappings brought out to the contacts of a sliding switch, the arrangement being very similar to that of the well-known end-cell battery-regulating switch.

Mr. Highfield points out that any form of rectifier introduces a harmonic into the primary. In most cases in Birmingham the plant runs in parallel with the rotary converter substations, and no effect of this nature has yet been noticed.

Mr. Taylor suggests that the method devised by Mr. J. R. Beard might have been used with advantage instead of developing a d.c. supply. It has, however, many disadvantages. If Mr. Taylor's static frequency-changer had a better power factor it is possible that the whole scheme of development to the outlying areas might have been on different lines.

Mr. Brazil points out that it was not necessary to run all the rectifier plant in a substation in series to give a three-wire supply. After the initial set has been installed, subsequent units could be connected across the outers only, with an efficiency of approximately 94 per cent.

Mr. Forrest points out that the correct title of this apparatus should be "Mercury-arc rectifier," and I agree that this is so. The exact number of relays and contactors required to operate a completely automatic mercury-arc rectifier as described in the paper is 8, whereas the number required to give the same control on a rotary converter set is approximately 30.

In reply to Mr. Jakeman, it would be possible to use induction regulators instead of the regulating device described, but the cost of this apparatus prevents its adoption for the small stations. The actual method used and described is comparatively cheap. The use of condensers would no doubt improve the power factor of rectifier units, but the additional cost is not warranted, since the power factor actually obtained is quite good.

Mr. Legge states that low-tension 25-period a.c. supply is being largely used in this country and abroad, and is considered quite satisfactory. Nevertheless, it cannot be said to be as good as direct current and, where the circumstances warrant the use of the latter, it is better to have direct current than alternating current at 25 periods for lighting. No doubt Mr. Legge and others who are giving a low-tension supply at 25 periods will welcome later a change to 50-period supply.

I agree with Mr. Goodman that 50-period supply by means of frequency-changers would be quite satisfactory in a case where there was no particular reason to convert to direct current. Mr. Goodman also raises the question of the voltage-rise on open circuit. This applies to the Brown-Boveri rectifier, and a special loading resistance is provided which is automatically switched in when the d.c. breaker opens. In the glass-bulb type of rectifier, however, this rise in the pressure does not, except in the case of traction units, take place at no load, and loading resistances for the purpose of preventing a rise in pressure are not required. In the case of the traction rectifiers no loading resistance is provided, because the stations run in parallel with rotary converters, and this prevents a no-load rise in pressure. It has, however, been decided to provide additional cathode chokes in all the traction rectifier plant, which chokes, together with small loading resistances to be switched in automatically when the load falls below 5 amperes, will prevent any rise of pressure at light loads.

Dr. Garrard is quite correct in stating that where a d.c. supply is required, an equally good case could be made out for converting from a 50-period supply. The largest size of a single rectifier unit is now stated to be 1 500 amperes at 600 volts, and is, of course, of the steel-cylinder type. I understand that developments are being made in the size of the glass-bulb type, but at present the unit of 150 amperes at 600 volts is the limit for commercial use. Unless there is some very special reason for using rectifiers, it will probably be found better and cheaper to use rotary converters for units above 500 kW. On the question of reliability Dr. Garrard is probably correct in stating that the rotary converter is on the whole more reliable than the mercury-arc rectifier, but more experience will probably make the rectifier plant equally as reliable as rotating plant.

Mr. Chattock explains more fully the reason for developing the outlying areas in Birmingham on d.c. lines instead of adopting special means for commencing a 50-period supply.

In reply to Mr. Angold, the fans and regulators require little attention, whereas a rotary converter necessarily does require a considerable amount of attention. The noise made by a bank of fans in a small substation seems rather loud inside the station, but, whereas the note of a rotary converter travels a considerable distance, the noise of the cooling fans cannot be heard a few feet outside the station.

Mr. Shuttleworth's remarks are extremely interesting. The decentralization now being carried out in Hull will be watched with great interest by engineers. A system of remote control of the various substations from one central point is on the right lines. His cost for maintenance and attendance of £0·07 per kW of plant installed is interesting, but further details would be required to enable a correct idea to be formed of the value of this figure. The glass-bulb type of rectifier would hardly be used in a substation up to 2 000 kW capacity, but in a substation of this capacity equipped with the steel-cylinder type of rectifiers there would be no difficulty in ensuring that the units took up their proper share of load.

In reply to Mr. Burgess, I would point out that the maximum-current relay for lowering the pressure is only

used in connection with the completely automatic booster sets which run in parallel with another supply.

Mr. James raises the question of ripples in the circuits fed from mercury-arc rectifiers, and I agree that the ripples have a greater amplitude than those from a rotary converter plant. Without giving oscillograph records it is difficult to supply full details of the amplitude of the ripples. The amplitude of the ripples varies with the load, but the ripples obtained from the glass-bulb rectifiers are comparable with those obtained with the Brown-Boveri steel cylinder. Reactances are provided in the anode circuits to enable two or more rectifier sets to run satisfactorily in parallel with each other. The experience in Birmingham shows that both the steel-cylinder rectifier and the glass-bulb rectifier run satisfactorily in parallel with rotary converters in the same substation.

In reply to Mr. Johnson, rectifiers are now being used in many places in this country and to a larger extent abroad. I should imagine that the "Tungar" rectifier is hardly likely to be used for heavy service work.

I find myself largely in agreement with Mr. Ratcliff's summing up of the general question.

Mr. Paxton mentions the interesting fact that the Brown-Boveri Co. now supply for use with the steel cylinder an indicating vacuum gauge which can be arranged to control the vacuum pump automatically, even if the rectifier is out of service. I have already dealt with the point raised by Mr. Paxton in regard to the connections for the regulator. Many speakers, including Mr. Paxton, have raised the question of the nature of the ripples in the three-wire rectifier circuit. The ripple in the circuit across the outers, in the case where two bulbs only are in service in the small three-wire substations, is six times the fundamental frequency of 25, viz. 150. Across one bulb only, i.e. 230 volts either positive or negative, the ripple is still practically six times the fundamental, and this is obtained by means of choking coils in the cathode circuit. Any current in the neutral, i.e. "out of balance" current, has a ripple of three times the fundamental. By cross-connecting when additional bulbs are added, a ripple of six times the fundamental frequency can be obtained as suggested by Mr. Paxton.

In reply to Mr. Clarke, failures of supply from any of the 25 substations now in service have been comparatively few in number. Many of the three-wire lighting substations have been in service for over 18 months without a single shut-down. The traction substations have given the most trouble, yet the supply has failed on but few occasions, and then only for a short period. Most of these interruptions have been due to the failure of parts of the installation other than the rectifiers, and the remainder have been due to faulty bulbs. When a short-circuit occurs in a bulb the bulb does not break, but the circuit breaker or fuses clear the fault. I am not in a position to give any information in regard to the life of the bulbs other than that already stated in the paper. A careful "life" record is being taken of all bulbs in service. No warning is given when a bulb is about to fail, but experience may show whether any warning signs may be found. It is obvious that some risk must be run in this connection. An interesting point is raised by Mr. Clarke in regard to the voltage regulator and its interlock with the excitation circuit of each bulb. In the case mentioned, it would be better if the voltage regulator continued to function, but in other cases there would be a danger of overloading the other bulbs. The details given of a change-over from direct to alternating current by using the Scott-connected transformer method is very interesting.

In reply to Mr. Townend, the glass-bulb type of rectifier was used for traction purposes because it was much cheaper, and also because duplicate plant was not necessary, owing to the plant being made up of a number of small units.

Mr. Sills states that an automatic rotary converter would have cost less for the 660-kW traction substation. This may be so, but spare plant would have to be provided, as any little trouble on the rotary converter or its transformer might have put the whole set out of commission for some time. In any case the cost of the building to house the plant would have been very much greater. It is true that the cooling fans—one for each bulb—constitute rotating plant, but the risk of breakdown is very small. For all intents and purposes it is correct to term the plant a static converter.

Mr. Preece suggests that in the early days the choice of 25 periods for the Birmingham supply was a mistake; nevertheless, rotary converters were not satisfactory at that time on a 50-period supply. I have a lively recollection of certain 50-period rotary converters the cost of repairs to which was at least three times as much as the maintenance costs of the rotary converters of the same period running on a 25-period supply.

Mr. Wilkinson gives his experience of plant of similar type to that described in the paper. It is very interesting and particularly pleasing to me to hear that other engineers are having satisfactory experience with this type of plant.

Mr. Cheetham endorses the opinion expressed in the paper in regard to the natural and inevitable development of automatic control gear for all types of electrical plant. He suggests that even generators may come later into the field of automatic control. He also raises the question of flash-overs in the glass bulbs. We have experienced no flash-overs in the 230-volt bulbs, but the higher-voltage bulbs have given some trouble in this respect. This has been due apparently to insufficient cooling of the bulbs.

Mr. Manighetti deals with the question of flash-over and points out the cause and the remedy. I feel confident that this apparent weakness will be entirely eliminated, and that the higher-voltage bulbs will be equally as reliable as the lower-voltage bulbs.

The various points raised by Mr. Lamb have already been dealt with.

Mr. Robinson agrees with the opinion expressed in the paper that a d.c. supply is preferable to a 25-period supply. He considers, however, that the automatically controlled rectifier unit as described in the paper is little less complicated than a rotary converter. I must differ entirely from Mr. Robinson in this matter. A comparison of Fig. 11, which is a complete wiring

diagram for the control gear, with the diagrammatic representation of the control gear for rotary converters (as for instance in Mr. Robinson's paper) will clearly indicate the greater simplicity of the rectifier control gear. The fact that less protection is provided for the rectifier plant than for a rotary converter is due to the plant itself requiring considerably less protection, and herein lies its great advantage. He would be a bold engineer who undertook to buy and connect up the control gear and relays necessary for the automatic operation of a rotary converter, yet this is what has been done in Birmingham, not for one automatic rectifier unit, but for several. On the question of the life of bulbs, the 8 000 hours mentioned in the paper has now been increased to over 12 000 hours, and there is no sign of the bulbs giving out.

I do not agree with Mr. Ross that the steel-cylinder Brown-Boveri type is not very well adapted to automatic control. On the contrary, a set in Birmingham has been so controlled with entire satisfaction for nearly three years. True, I pointed out in the paper the drawback caused by the necessity to reform under certain conditions, but this is not now necessary in the later plant. The other drawback mentioned by Mr. Ross has also been removed by the means mentioned by Mr. Paxton.

The Brown-Boveri Co. do not now provide fuses between the transformer windings and the rectifier anodes, but rely on the main oil switch and d.c. circuit breaker to clear a short-circuit in the cylinder. Mr. Ross draws attention to the low cost of the d.c. switchgear for the traction station described in Appendix 3. Actually the d.c. panel consists simply of angle-iron framework carrying three automatic reclose circuit breakers which control the supply to three outgoing feeders. There are no ammeters or knife switches in the feeder circuits. The apparatus was bought and erected on the angle-iron framework. This accounts for the low cost of this gear. The later substations, however, were equipped with a d.c. board having slate panels and a knife switch and ammeter in each feeder circuit. It is true that we now have in hand a number of automatic rotary converter substations for both traction and lighting supplies. Above a capacity of 500 kW and where the question of noise need not enter into consideration, the rotary converter is likely to be used in preference to glass-bulb rectifiers.

In reply to Mr. Williams, the overload capacity of the glass bulbs has not yet been fully determined. From experience it is known that an overload of 25 per cent for two hours will be carried satisfactorily. An overload of 50 per cent has been noted on the traction bulbs for short periods.

Mr. Breach points out that in one of the slides shown, illustrating an installation of mercury-arc rectifiers, an oil circuit breaker is shown controlling the supply to a d.c. distributor. This happens to be the only case where an oil breaker is used, and in this case it was used because at the time a suitable air-break totally-enclosed breaker was not available. The standard practice is now to use switch fuses (as described in the paper) or air circuit breakers for this purpose. The particular breaker referred to has not opened in practice, but it is guaranteed to be satisfactory for its present duties. We are adopting a similar method to that successfully used in Liverpool for removing the interference—due to induction—on the Post Office telephone circuits. I am hoping for similar satisfactory results in our particular case.

The question of loading resistances on the traction sets has been dealt with already. The reclose circuit breakers on the traction circuits can open an indefinite number of times and reclose when faulty conditions have been removed. Before handling a faulty cable or overhead line which may have fallen, the practice is to open the section switch in the street pillars controlling the faulty line. The breaker will not reclose until this has been done, unless of course the fault has cleared itself in the meantime. Mr. Breach's description of the method adopted in Liverpool for substation ventilation is very interesting and well worth consideration. I regret that in the advance copies of the paper, the fuses in circuit between the transformer secondary and the bulb in Fig. 5 were omitted. These have now been added. A fault on one bulb does not necessarily affect other bulbs in circuit with it.

THE CURRENT RATING OF SINGLE-CONDUCTOR, LEAD-COVERED, LOW-TENSION CABLES ON SINGLE-PHASE ALTERNATING-CURRENT CIRCUITS.

By S. W. MELSOM, Associate Member, and W. E. BEER, Student.

[FROM THE NATIONAL PHYSICAL LABORATORY.]

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SUMMARY.

Single-core cables in single-phase systems are bonded to annul the high voltages that would otherwise exist between the lead sheaths when the latter are open-circuited, but bonding brings into being induced currents which may reach high percentages of the conductor current and reduce the safe current-carrying capacity.

In this paper some theoretical considerations of the losses of energy occurring in single-core cables on alternating-current circuits are given, and their effect on the line characteristics are noted.

In the first portion of the paper the results of measurements carried out on a single-phase system in air to determine the loadings for a given temperature-rise are tabulated and represented graphically. In a series of experiments the following factors were varied one at a time:—

(1) Current flowing in the system.
(2) Spacing of conductors in an iron-free neighbourhood.
(3) Spacing of conductors with iron interposed.
(4) Cable cross-section.

It is noted that, taking into account the mutual heating effect of two cables in proximity and the heating due to alternating currents flowing in the system, there is an arrangement of the cables in a horizontal plane which gives the maximum value of permissible current loading.

It is generally accepted that temperature-rise is the most important limiting factor in power-cable operation, and the recent Report on the Research on the Heating of Buried Cables * has been based on this assumption. Any study of cable characteristics must therefore take account of heating, and these notes have for their object the consideration of the heating, and consequent limitation of the current loading, of cables in single-phase systems.

Modern practice requires that the lead sheaths of single-conductor cables laid underground must be continuous throughout and bonded across at intervals; for installing in a building the lead sheaths must again be continuous, being connected at every joint, with the possibility of bonding across at intervals in the length by means of joint boxes, structural metal-work to which the cables or joint boxes are attached, or the metal clips used to support the cables.

The practical case, therefore, on which any limitation of the use of such cables must be based, is that in which the sheaths of a pair of cables are bonded at frequent intervals.

In addition to the core and sheath losses which occur in alternating-current circuits there is the mutual heating effect when the cables are in proximity, which arises in all cases. This effect is greatest with the lead sheaths in contact, and rapidly decreases until it becomes negligible. This occurs when the distance between the cable axes is approximately five times the diameter of the lead sheath. On the other hand, the losses in the lead increase rapidly as the distance between the cable axes increases. Hence for any single-phase power system there is a critical distance between the cable axes for which the total heating effect is a minimum and which therefore gives the maximum permissible loading.

* *Journal I.E.E.*, 1921, vol. 59, p. 181, and 1923, vol. 61, p. 517.

EXPERIMENTAL WORK.

The limit of heating has been taken as 35 deg. C. rise of conductor temperature, but this figure is simply taken in order to afford a basis of comparison and not necessarily as a final value of permissible temperature-rise for operating conditions.

In general, the temperature-rise of the conductor in an iron-free neighbourhood varies very nearly with the square of current intensity.

As a preliminary experiment with the object of providing a reference, a series of tests was carried out to determine the permissible direct-current loadings for the low-tension lead-covered cables considered in detail below.

The arrangements of the tests were, in the case of cables laid in a neighbourhood free from iron, designed to approximate to practical conditions. The other experiments described later, in which the proximity effect of extraneous metal is taken into account, involved conditions in some cases possibly more severe than those occurring in practice.

In the series of experiments the results of which are given in Tables 1 to 12, two lengths of cable of each size tested, forming the lead and return, were laid straight out on the wooden floor of an evenly ventilated, draught-free, constant-temperature room, and in an iron-free neighbourhood. A transformer T (see Fig. 1) fed through an adjustable series regulator AR from an alternating-current supply at 50 periods per sec. (wave-shape ordinary), supplied the cores through a change-over switch and a current transformer CT; the latter, in combination with an ammeter A, measured the conductor current. By throwing over the change-over switch the cable was fed with direct current from

a heavy-current battery, a standard resistance being included in this circuit for measuring purposes. In this way it was possible to supply the cable system with either alternating or direct current of any desired value.

The ends of the lead sheaths were bonded by copper bars of $1\frac{1}{4}$ in. $\times$ $\frac{3}{8}$ in. cross-section (the contact resistance

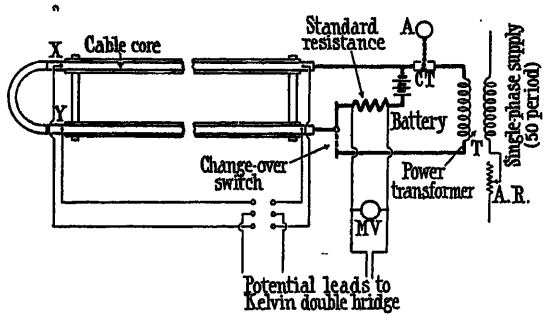

FIG. 1.—Diagram of connections for current loading.

being negligible) at right angles to the cable axes, whilst the ends X and Y of the cable were joined by a copper conductor loop of cross-section equal to that of the core, in order to ensure that there should be no extraneous heating or cooling.

METHODS OF MEASUREMENT.

The temperature-rise of the cables was determined by measuring the increase of conductor resistance by means of a Kelvin double bridge, and the surrounding air temperature was observed by means of a number of thermometers placed at the same level as the cable but about 3–4 ft. from it. The temperature coefficient used in calculating the rise of temperature was taken from B.S.S. No. 72 (1917).

Other investigators of losses in single-phase cable systems have determined them by means of voltmeter, ammeter and wattmeter, but the thermal method of test employed is well known and the principle of measuring the relative amounts of heat produced when the test length is traversed by two types of current is used in the determination of the resistance of wires to currents of high frequency, and, as here used, consists in comparing the direct and alternating currents necessary to produce the same temperature-rise of the conductor of the cable under test.

Having established a steady state in which, with the testing current maintained constant, a constant temperature-rise is obtained; then for equal heating in the two cases

$$I_1^2 R_1 = I^2 R$$

where I_1 = alternating-current loading in amperes,
R_1 = resistance of cable to alternating current,
I^2 = direct-current loading in amperes,
R = resistance of cable to direct current.

I_1, I and R can all be accurately determined; the first two by precision ammeters, and the last by the Kelvin double bridge. R_1/R is therefore immediately determinable.

The heating is brought about by actually loading the cable, and therefore in the experiments the same distribution of heat is obtained as in actual working. The true permissible loading is accurately ascertained and the only measurements involved are those of current, resistance and temperature. In the heating method slight differences may arise under slightly different conditions of ambient temperature, a lower initial room temperature tending to cause a slightly higher temperature-rise, but such differences do not appreciably affect the general results and under proper conditions a high degree of accuracy is obtainable. Among the advantages of the method it is to be noted that the observations made refer only to that part of the circuit in which we are interested, and so render corrections for the remainder of the circuit unnecessary. The observations, however, require a considerable time, and have, moreover, to be made under special conditions which are often not available in practice.

In the case of the tests with alternating current, the measurement of resistance was made by changing over to direct current immediately before making an observation, the time taken being about 20 seconds.

The temperatures of the lead sheath were determined by means of thermo-couples, the hot junctions being embedded in the sheaths. The mean temperature coefficient of lead at 20° C. was taken as 0·00385. This is based on a large number of observations on cable sheaths.

The effect of iron in the immediate vicinity of the cables was investigated by laying the conductors alongside lengths of iron of different cross-sections, as shown in Figs. 9 and 10, the axial distance being varied and the temperature-rise of the cable cores being determined as before. Three sizes of cable of sections 0·1 sq. in., 0·3 sq. in., and 0·5 sq. in. were tested under these conditions, both with direct current and with alternating current at 50 periods per sec.; the comparison in all cases refers to a temperature-rise of 35 deg. C., whence the ratio R_{eff}/R follows immediately.

Then, with the testing apparatus arranged as described, a series of experiments was carried out varying the following factors one at a time:—

(1) Current flowing in the system.
(2) Spacing of conductors in iron-free neighbourhood.
(3) Spacing of conductors with iron interposed.
(4) Cable cross-section.

The usual precautions were taken to avoid end-effects.

RESULTS.

For a given temperature-rise, say 35 deg. C., the conductors of a given single-phase system with lead sheaths short-circuited will carry various loadings according to the proximity of the return cable, and also according to the proximity of the system to neighbouring masses of iron. Under certain conditions the losses in the sheath and extraneous iron may be greater than the copper loss. The variations of the loadings with direct current from those given in the Report already referred to are due to the individual characteristics of the various cables and to the conditions under which they were laid.

The largest cable on which a full series of tests was

carried out was a low-tension single-conductor paper-insulated plain lead-sheathed cable having a cross-section of 0·5 sq. in.

Here the number and diameter of wires comprising the conductor = 61/0·101 in.

Maximum number of component wires on a diameter = 9.

Overall diameter of complete strand = 0·909 in. = 2·309 cm.

Actual copper area = 0·4885 sq. in. = 315 sq. mm.

Diameter over paper insulation = 2·86 cm.

Thickness of lead = $\frac{1}{2}$ × 0·5 cm = 0·25 cm.

Diameter over lead = 1·322 in. = 3·36 cm.

Resistance of conductor per 1 000 yards at 15·6° C. = 0·0497 ohm.

Resistance of lead sheath per 1 000 yards at 15·6° C. = 0·81 ohm.

Approximate age = 12 years.

A single cable.—Typical heating curves corresponding to various steady d.c. and a.c. loadings for a single

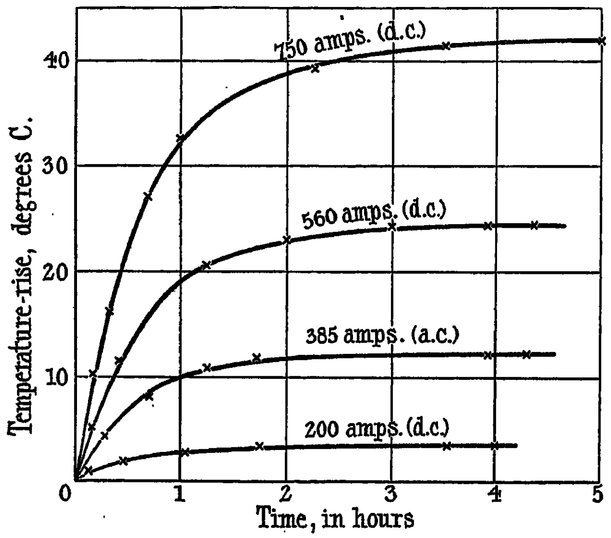

FIG. 2.—Curves showing temperature-rise of a 0·5 sq. in. single low-tension cable tested in air.

cable in air and obtained by running until a final maximum temperature-rise above that of the surrounding air was established, are given in Fig. 2. It will be observed that the time required for each test was between 4 and 5 hours.

The series of values of final temperature-rise and their corresponding current loadings are plotted in Fig. 3, from which the loading for a single cable in air * for any temperature-rise can be obtained by interpolation. It will be seen that the points all lie on the same curve, showing that under this particular condition there is no appreciable difference between direct current and alternating current at 50 periods per sec.

Two cables laid side by side.—The results of the experiments made to determine the mutual heating effect of two such cables in air are shown in Fig. 3.

* By "in air" is to be understood that the cable is lying on the wooden floor of a room.

Summary of results.—Assuming 35 deg. C. to be the permissible temperature-rise of the conductor :—

For a 0·5 sq. in. cable laid singly under the conditions stated above, current loading = 678 amperes direct current, or alternating current at 50 periods per sec.

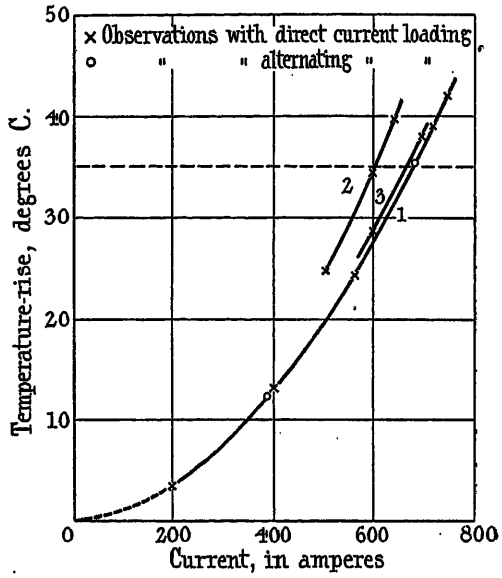

FIG. 3.—Curves showing temperature-rise of various arrangements of 0·5 sq. in. single-conductor cable tested in air.

Curve 1 refers to a single cable.
Curve 2 refers to two single-core cables laid side by side with axes 3·36 cm (1·3 in.) apart and loaded with direct current.
Curve 3 refers to two single-core cables with axes 9 cm (3·5 in. apart and loaded with direct current.

For a pair of 0·5 sq. in. single cables in air laid parallel throughout their length and under the same conditions as the above, the values given in Table 1 apply.

TABLE 1.

Distance between axes		D.C. current loading	Pair d.c. loading / Single d.c. loading
in.	cm	amps.	per cent
1·3*	3·36*	604	87·8
3·5	9·0	670	97·5
4·75	12·0	673	99·3
8·25	21·0	678	100
12·0	30·4	678	100

* Cables touching.

The first and last columns of this table are shown by curve A in Fig. 4.

The calculation of the mutual heating effect of a pair of cables in air is not simple when it is remembered that the problem is one of a single cable in an infinite medium together with a local disturbance. Further, a solution would be only of theoretical interest and the experimental curves in the paper relating to the problem of mutual heating are included solely on this account. It may be noted that at distances between axes of about 5 diameters, the effect is negligible.

The problem of the mutual heating of buried cables is of course of great interest, but this has been fully dealt with elsewhere. In general, the effect will be to give a curve of the same type as that obtained in air but with the initial portion increasing at a much lower rate.

Two single-phase cables (lead and return) laid up together.—The results of the tests corresponding to the practical case where the two 0·5 sq. in. single-phase cables carrying alternating current and having their sheaths bonded are laid up together or fairly close to each other, are given in Table 2 and are summarized in Fig. 4, curve B.

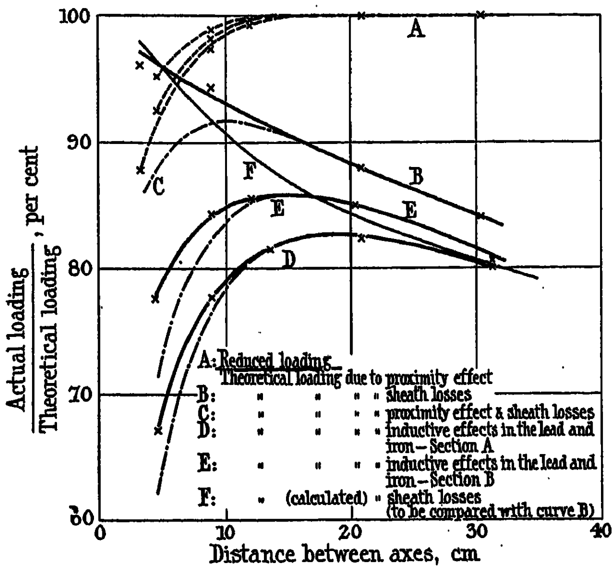

FIG. 4.—Curves showing the relation between (actual loading)/(theoretical loading) and axial spacing for a 0·5 sq. in. single-phase cable system tested in air.

TABLE 2.

Distance between axes		Current loading at 50 periods per sec.	Temperature-rise	
			Copper	Lead
in.	cm	amps.	deg. C.	deg. C.
1·3	3·36	500	26·3	—
1·3	3·36	600	37·3	28·5
1·3	3·36	650	43·1	—
3·5	9·0	600	31·56	23·4
3·5	9·0	660	37·7	—
8·25	21·0	600	35·4	—
12·0	30·4	600	38·25	28·9
12·0	30·4	520	29·4	—

Reducing these to the common value of a temperature-rise of 35 deg. C., the results given in Table 3 are obtained.

The results given in Table 3 are represented graphically by curve B in Fig. 4. The last column gives the ratio of the effective resistance to the ohmic resistance of the conductor.

Curve C in Fig. 4 represents the effects due to mutual heating and lead-sheath losses combined. The shape of this curve is interesting as giving an indication of the variation of permissible loading with distance between axes, and it is to be noted that the maximum possible loading occurs when the axes are separated by about 10 cm. But, as has already been pointed out, curve A applies to cables laid along the wooden floor of a room; for the case of buried cables the ordinates would be rather different. Curve B, however, will apply equally well to buried cables.

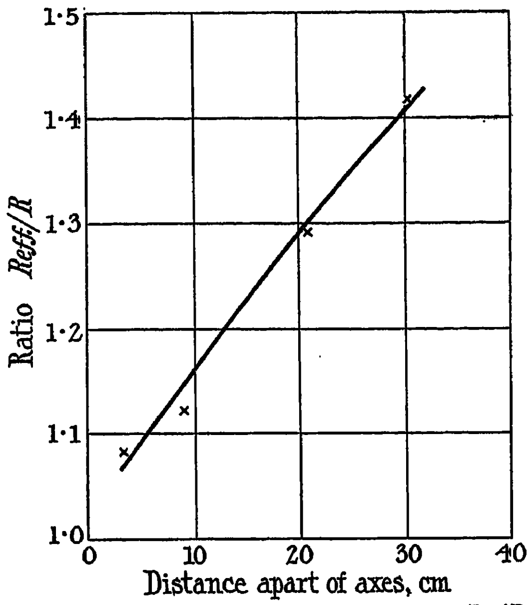

FIG. 5.—Curve showing the relation between $R_{eff.}/R$ and axial spacing in cm for a 0·5 sq. in. single-phase cable system tested in air and in an iron-free neighbourhood.

Considering curve B, it is seen that the effect of lead-sheath losses increases as the conductors get further apart, resulting in a decreased loading of the cable for a given temperature-rise. For the case of the lead sheaths bonded at both ends the induced current is a maximum. Fig. 5 shows how the effective resistance offered to alternating current at 50 periods per sec. increases with the spacing (with lead sheaths bonded),

TABLE 3.

Distance between axes		Current loading		A.C. loading / D.C. loading	$\frac{R_{eff.}}{R}$
		d.c.	a.c.		
in.	cm	amps.	amps.	per cent	
1·3	3·36	604	580	96·1	1·08
3·5	9·0	670	632	94·4	1·12
8·25	21·0	678	596	88·0	1·29
12·0	30·4	678	570	84·1	1·42

the ohmic resistance of the conductor being 0·0575 ohm per 1 000 yards at 55° C.

Presence of extraneous iron.—Some tests were undertaken with the object of determining the safe current-carrying capacity of the cable under consideration when the two units of a single-phase system embraced ironwork in a definite manner. The results with lead sheaths bonded are given below.

(1) *Employing section of steel rail* (*see section A, Fig.* 9).—Weight per foot length = 22 lb. approx. The actual observations are given in Table 4, and these are reduced to a common value of temperature-rise in Table 5.

TABLE 4.

Testing current	Distance apart of axes		Temperature-rise Copper	Temperature-rise Lead
amps.	in.	cm	deg. C.	deg. C.
667 (d.c.)	1·8	4·63	34·59	—
488·5 (a.c.)	1·8	4·63	40·3	—
450 (a.c.)	1·8	4·63	34·9	—
661 (d.c.)	1·8	4·63	33·9	26·5
458 (a.c.)	1·8	4·63	36·15	—
700 (d.c.)	3·5	9·0	35·27	—
550 (a.c.)	3·5	9·0	37·0	—
700 (d.c.)	5·3	13·5	34·3	—
755 (d.c.)	5·3	13·5	39·85	—
520 (a.c.)	5·3	13·5	29·1	—
600 (a.c.)	5·3	13·5	38·06	—
670 (d.c.)	8·25	21·0	31·8	—
578 (a.c.)	8·25	21·0	34·7	—
456 (a.c.)	12·5	31·6	23·0	18·6
704 (d.c.)	12·5	31·6	34·9	—
580 (a.c.)	12·5	31·6	36·6	29·2
Sheaths not	*bonded.*			
669 (a.c.)	12·5	31·6	32·3	23·5
700 (a.c.)	12·5	31·6	35·0	—

TABLE 5.

Distance between axes (*x*)		Current loading d.c.	Current loading a.c.	A.C. loading / D.C. loading	$\frac{R_{eff.}}{R}$
in.	cm	amps.	amps.	per cent	
1·8	4·63	670	450	67·2	2·22
3·5	9·0	697	534	77·8	1·71
5·3	13·5	704	574	81·5	1·49
8·25	21·0	704	580	82·4	1·47
12·5	31·6	704	564	80·1	1·56

The values for direct current given in Table 5 are not quite the same as those in Table 3. This difference is due to the cable being supported off the floor, and to the proximity of the iron. In order, however, to determine the magnitude of the inductive effects the comparison is made with values of both alternating and direct current obtained under identical conditions of laying.

(2) *Employing section of steel girder* (*see section B, Fig.* 10).—This is a type of girder commonly employed in building construction, weighing approximately 8·2 lb. per foot length.

TABLE 6.

Lead Sheaths Bonded.

Testing current	Distance apart of axes (*r*)		Temperature-rise of cores
amps.	in.	cm	deg. C.
740 (d.c.)	1·7	4·3	43·3
640 (d.c.)	1·7	4·3	33·2
561 (a.c.)	1·7	4·3	42·4
500 (a.c.)	1·7	4·3	33·6
702 (d.c.)	3·5	9·0	35·4
580 (a.c.)	3·5	9·0	34·1
702 (d.c.)	4·75	12·1	34·5
619 (a.c.)	4·75	12·1	36·5
724 (d.c.)	8·25	21·0	36·2
586 (a.c.)	8·25	21·0	32·8
620 (a.c.)	8·25	21·0	36·6
475 (a.c.)	12·5	31·6	24·8
560 (a.c.)	12·5	31·6	33·3
600 (a.c.)	12·5	31·6	37·8
678 (d.c.)	12·5	31·6	31·9
750 (d.c.)	12·5	31·6	38·7

TABLE 7.

Distance apart of axes		Current loading d.c.	Current loading a.c.	A.C. loading / D.C. loading	$\frac{R_{eff.}}{R}$
in.	cm	amps.	amps.	per cent	
1·7	4·3	658	510	77·5	1·67
3·5	9·0	699	589	84·3	1·41
4·75	12·1	708	605	85·5	1·38
8·25	21·0	711	605	85·1	1·38
12·5	31·6	711	574	80·6	1·53

The results given in Tables 5 and 7 respectively are shown in Fig. 4, curves D and E.

From the graphs it is seen that the current loading is greatly reduced owing to the strengthening of the field by the iron. The curves are somewhat similar in shape, the distance between the axes corresponding to the maximum loading increasing as the mass of iron per foot run increases. Also, with spacings greater than 30 cm the curves tend to coincide and run parallel to the corresponding curve for the system in an iron-free neighbourhood. With ordinary cable spacings, however, the reduced loading does not appear to follow any simple law, and it is clear that the losses and consequent heating will depend largely on the configuration of the neighbouring iron, and therefore, if the installation of a single-phase system in the vicinity of magnetic material is contemplated, each case should receive careful and separate attention with a view to the determination of its probable characteristics when working.

In connection with the tests employing section A, an experiment was carried out with the cable embracing the steel rail, and axes 31·6 cm (12·5 in.) apart, but with the lead-sheath circuit open. No difference was observed between the heating with alternating current and direct current, though on bonding, while the alternating current was flowing, a heavy spark showed the presence of dangerous induced sheath voltages.

Low-tension single-conductor paper-insulated plain lead-sheathed cable of 0·3 *sq. in. cross-section.*

Number and diameter of wires comprising conductor = 37/0·1038 in.

Maximum number of component wires on a diameter = 7.

Overall diameter of complete strand = 0·7266 in. = 1·847 cm.

Actual copper area = 0·3126 sq. in. = 202 sq. mm.

Diameter over paper insulation = 0·92 in. = 2·34 cm.

Thickness of lead = 0·24 cm.

Diameter over lead = 1·11 in. = 2·82 cm.

Resistance per 1 000 yards at 15·6° C. = 0·078 ohm.

A series of observations was made similar to those carried out on the 0·5 sq. in. cable in an iron-free neighbourhood, and in general the same order is followed.

A single cable.—As in the case of the larger cable, there is no appreciable difference between direct and alternating current at 50 periods per sec. Current loading (a.c. and d.c.) for a rise of 35 deg. C. = 512 amperes.

Mutual heating effect of a pair of cables.—With direct current for a temperature-rise of conductor of 35 deg. C. the values are given in Table 8.

TABLE 8.

Distance between axes		D.C. current loading	Pair d.c. loading / Single d.c. loading
in.	cm	amps.	per cent
1·11*	2·82*	457	89·2
3·3	8·4	506	98·8
7·0	17·8	512	100
12·5	31·7	512	100

* Cables touching.

Table 9 gives the values with both alternating current (50 periods) and direct-current for various distances apart for a rise of temperature of 35 deg. C.

TABLE 9.

Distance between axes		Current loading		A.C. loading / D.C. loading	$\frac{R_{eff.}}{R}$
		d.c.	a.c.		
in.	cm	amps.	amps.	per cent	
1·11*	2·82*	457	450	98·5	1·03
3·3	8·4	506	476	94·0	1·13
7·0	17·8	512	469	91·5	1·20
12·5	31·7	512	456	89·0	1·26

* Cables touching.

The results are plotted in Figs. 6 and 7, and these curves show that the performance of a 0·3 sq. in. cable in an iron-free neighbourhood is not radically different from that of a 0·5 sq. in. cable under the same conditions of laying. As would be expected, the inductive effects are less pronounced than with the 0·5 sq. in.

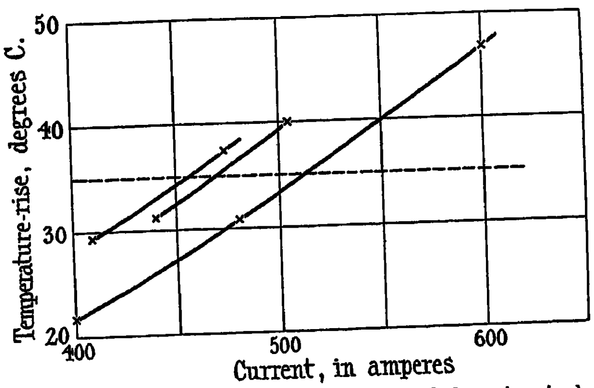

FIG. 6.—Curves of temperature-rise for a 0·3 sq. in single-phase cable system tested in air.

cable. The maximum loading for a cable of this size in air occurs with a spacing of about 9 cm. In Fig. 7, curves A and B refer to the measured and calculated values respectively. There is close agreement over the practical range of spacings, the greatest discrepancy occurring when the cable sheaths are touching and also at the largest spacing.

The ratio R_{eff}/R increases with the distance between the axes, as in the previous case.

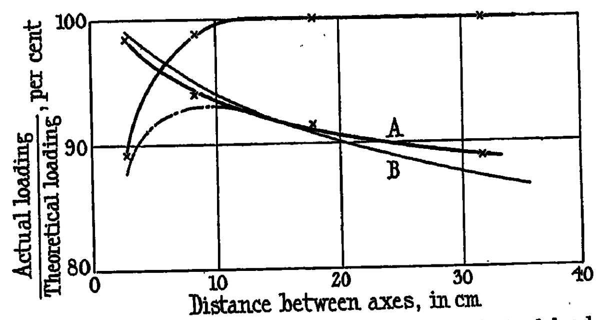

FIG. 7.—Curves showing the relation between (actual loading)/(theoretical loading) and axial spacing for a 0·3 sq. in. single-phase cable system tested in air.

The corresponding figures for a 0·1 sq. in. vulcanized-rubber plain lead-sheathed cable are as follows :—

Number and diameter of wires comprising conductor = 19/0·083 in.

Maximum number of component wires on a diameter = 5.

Overall diameter of complete strand = 0·425 in. = 1·08 cm.

Actual copper area = 0·103 sq. in.

Diameter over rubber insulation = 0·582 in. = 1·48 cm.

Thickness of lead = ½ × 0·15 in. = ½ × 0·38 cm.

Diameter over lead = 0·732 in. = 1·86 cm.

Resistance per 1 000 yards at 15·6° C. = 0·25 ohm.

A single cable lying along the wooden floor of a room.—Current loading (a.c. 50 periods, and d.c.) for a rise of 35 deg. C. = 245 amperes.

Mutual heating effect of a pair of cables.—With direct current for a temperature-rise of conductor of 35 deg. C. the values are given in Table 10.

TABLE 10.

Distance between axes		D.C. current loading	Pair d.c. loading / Single d.c. loading
in.	cm	amps.	per cent
0·73	1·86	210	85·7
1·65	4·2	229	93·4
2·9	7·4	240	97·9
7·7	19·5	245	100
12·1	30·8	245	100

Table 11 gives the values with both alternating current (50 periods) and direct current for various distances apart for a rise of temperature of 35 deg. C.

TABLE 11.

Distance between axes		Current loading		A.C. loading / D.C. loading
		d.c.	a.c.	
in.	cm	amps.	amps.	per cent
0·73	1·86*	210	207·5	98·8
2·9	7·4	240	235	98·0
7·7	19·5	245	236·5	96·5
12·0	30·8	245	234	95·5

* Cables touching.

The above results are graphically represented in Fig. 8, in which A and B indicate the measured and

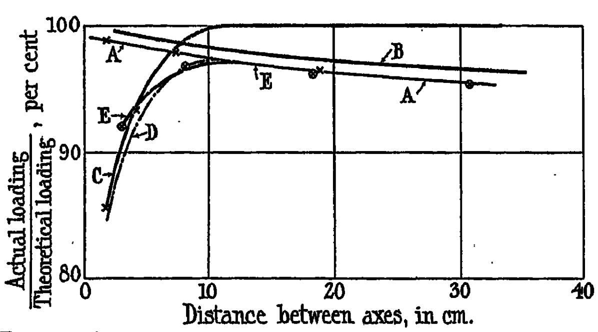

FIG. 8.—Curves showing the relation between (actual loading)/(theoretical loading) and axial spacing for a 0·1 sq. in. single-phase cable system tested in air.

calculated values respectively. In this case the difference between the two curves is practically constant, the experimental values indicating a rather lower … Curve C refers to mutual heating in air with … rent, and D is the resultant of A and C, giving a maximum loading in air corresponding to an axial spacing of about 12 cm.

The effect on the current-carrying capacity when the iron section A (Fig. 9) was interposed throughout the whole of the test lengths of cable was investigated as in the case of the 0·5 sq. in. cable. The results obtained are given in Table 12.

TABLE 12.

Distance between axes		A.C. loading / D.C. loading
in.	cm	per cent
1·23	3·13	92·0
3·2	8·2	96·7
7·25	18·37	96·3
12·2	30·9	95·4

The values in Table 12 refer to a temperature-rise of conductor of 35 deg. C., the lead sheaths being bonded, and are shown graphically by curve E in Fig. 8.

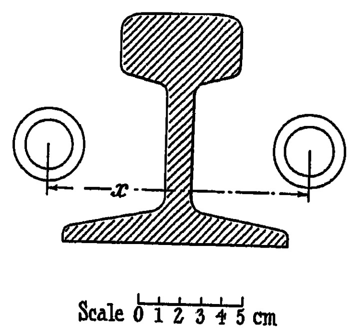

FIG. 9.—Section A.

Permissible current loading for various conditions of laying.—The composite effect of spacing the cables apart and the induction effects with and without iron are shown in Tables 13 and 14, in which the loading under the different conditions is expressed as a percentage of the standard value for two cables laid up

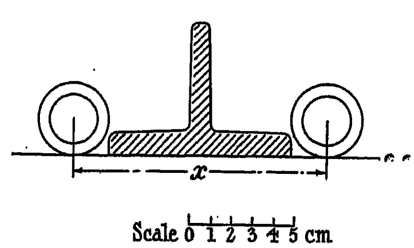

FIG. 10.—Section B.

close to and touching each other as is given in the I.E.E. Wiring Rules tables (7th edn.).

It will be noted that with the 0·1 sq. in. cable the current-carrying capacity is in most cases increased by increase of the spacing and by clamping the cable to iron. In the case of the 0·5 sq. in. cable, however, the loading with alternating current is in most cases substantially

reduced and, in particular, under the not unusual condition of two cables being clamped to an iron girder, the rating is only 72 per cent of the standard. Attention should be drawn to the fact that if a cable laid under these conditions were run at the standard rating, this temperature-rise would be 96 deg. F. instead of the 50 deg. F. allowed by the I.E.E. Wiring Rules.

TABLE 13.

For a Pair of 0·5 sq. in. Cables (Go and Return).

Condition of laying	Type of current loading	Current loading in terms of standard value in I.E.E. Wiring Rules (7th edn.)
Cables touching without iron	D.C.	100
	A.C. (50 periods)	96
Cable axes at 1·8 in. apart without iron	D.C.	104
	A.C. (50 periods)	100
Cable axes at 12 in. apart without iron	D.C.	112
	A.C. (50 periods)	94
Cable axes at 1·8 in. apart with iron section A (Fig. 9) interposed	D.C.	107
	A.C. (50 periods)	72
Cable axes at 12 in. apart with iron section B (Fig. 10) interposed	D.C.	112
	A.C. (50 periods)	91

TABLE 14.

For a Pair of 0·1 sq. in. Cables (Go and Return).

Condition of laying	Type of current loading	Current loading in terms of standard value in I.E.E. Wiring Rules (7th edn.)
Cables touching without iron	D.C.	100
	A.C. (50 periods)	99
Cable axes at 1·23 in. apart without iron	D.C.	106
	A.C. (50 periods)	105
Cable axes at 12·0 in. apart with and without iron	D.C.	117
	A.C. (50 periods)	111
Cable axes at 1·23 in. apart with iron	D.C.	113
	A.C. (50 periods)	105

The above refers only to comparison with the standard rating. Actually, as shown by Figs. 4, 7 and 8, in which the whole of the results are given, the comparison between alternating and direct current for any one condition is more unfavourable to alternating current. Reference to these figures shows that there is a critical spacing for a particular size of cable and method of laying that will give the maximum loading. This is approximately 10 cm (4 in.) where there is no iron, and increases up to 20 cm in the proximity of a heavy section of iron.

The values in Tables 5, 7 and 12 and in Figs. 4 and 8 are for cables laid on an iron girder, where the rating will, of course, be affected by the extent to which the cables are in intimate contact with the iron. They must therefore be regarded as being only approximate. It is, however, satisfactory to find that the cables of 0·1 sq. in., and less, can be used up to the standard rating under all conditions, but it is clear that special precautions must be taken for cables larger than this.

LOSSES IN LEAD SHEATH.

The calculation of the induced E.M.F.'s in the lead sheaths of single-core cables carrying alternating current is facilitated by considering the system as a transformer in which the primary is the copper conductor and the secondary is the lead sheath, each of one turn.

The conception of a single-phase system as being equivalent to a transformer with short-circuited secondary, and with zero reactance in the secondary, was elaborated by Clark and Shanklin.* The appendixes to that paper deal very fully with the characteristics of single-conductor cable.

For a discussion of the magnetic interlinkage between two circuits, "Theory and Calculation of Electric Currents," by J. L. La Cour and O. S. Bragstad (translated by S. P. Smith, D.Sc.) should be consulted. On page 116 the authors state: "In electromagnetic machinery, we have nearly always to deal with a main flux and a stray flux, or with corresponding magnitudes, viz. the coefficients of mutual and of stray induction. This is due to the fact that these fluxes are actually present in the machine, whilst the fluxes corresponding to the coefficients of self-induction do not as a rule exist, and consequently are not easy to calculate. Moreover, the former method of calculation has the advantage that all machines can be analytically replaced by equivalent electric circuits. On the contrary, the reactance $2\pi cL_1$ (where c = frequency and L_1 = coefficient of self-induction of the primary winding) is not at all confined to one electric circuit, but is distributed over two circuits in which different currents flow. Consequently, with machines, it is not convenient to work with the reactance due to self-induction. In the case of mains or other similar circuits, however, where little or no iron at all is present, the conditions are different. Here the reaction of the currents in neighbouring conductors is often so small that the stray flux is larger than the main flux. In such cases it is best to use the coefficients of self-induction, and estimate as nearly as possible, by approximate calculations and experiments, the damping effect of secondary currents in the neighbourhood or in the conductors themselves."

Clark and Shanklin,† Capdeville ‡ and other investigators have, for the purpose of extending the treatment to certain polyphase systems, considered one cable and the neutral. In the present paper attention is confined to single-phase lines consisting of a pair of cables, go and return.

The question of single-phase lead-sheathed cables can be conveniently approached by a consideration of the various coefficients of induction involved, and this is the course adopted in the present case.

* Bibliography, item (2). † *Ibid.*, item (2). ‡ *Ibid.*, item (1).

In considering the losses in the lead, let Fig. 11 represent a single-phase system. Let the distance between the axes of the two cables be denoted by D, and let the conductors of length l be traversed by a current i_a (absolute units).

The magnetic field at any point P is the resultant of the two magnetic fields at point P due to the currents in the two conductors.

To take into account the effect of the various linkages we must therefore use an expression of the form $\Phi_x I_x$, where Φ_x is the flux linking the current I_x.

In this treatment there are three inductances to be determined, viz.,

(1) The inductance of the copper circuit comprising the two conductors;
(2) The inductance of the lead circuit comprising the two lead sheaths; and
(3) The mutual inductance between the copper and lead circuits.

Taking these in order:—

(1) In Fig. 11 let r_1 be the radius of the conductor, and r_2 and r_3 respectively the internal and external

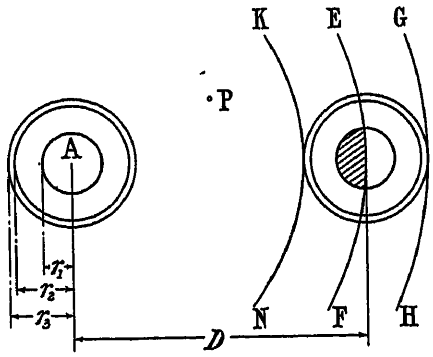

FIG. 11.—Single-phase circuit of a pair of single-core lead-covered cables lying parallel to one another in a horizontal plane.

radius of the lead sheath. It is assumed that the length of the line is great compared with the axial spacing.

The field H outside conductor A at a distance x from the centre of A is $2i_a/x$. Consider a length of 1 cm.

$$\text{Then flux} = d\Phi = (2i_a/x)dx \quad \text{and} \quad \Phi = \int_{r_1}^{D}(2i_a/x)dx$$

It should be noted that in connection with the upper limit D we ought actually to take the mean between GH and KN, which is EF (Fig. 11), and therefore the shaded area is involved. But the usual assumption in these calculations is that the core diameters are small compared with the distance apart of the axes. With such assumptions D is quite sufficient. It is interesting also to note that the result obtained by these limits is strictly correct, the slight apparent discrepancy being compensated for by the distortion of the magnetic whirl axes due to the proximity of the two conductors.

Hence
$$L_{c_1} = 2\log_e x\Big]_{r_1}^{D} = 2\log_e\frac{D}{r_1}$$

Now consider the flux inside conductor A.

Remembering that the magnetomotive force = work done in carrying unit pole once round the circuit we have:—

At distance x_1 from centre

$$H \times 2\pi x_1 = 4\pi i_a\frac{x_1^2}{r_1^2}$$

Therefore
$$H = 2i_a\frac{x_1}{r_1^2}$$

If $d\Phi'$ is the flux traversing an element comprised between the cylinders of radii x_1 and $(x_1 + dx_1)$, then

$$d\Phi' = \frac{2i_a}{r_1^2}x_1 dx_1$$

The current linked by $d\Phi'$ is $\frac{x_1^2}{r_1^2}$

$$\text{Therefore linkages due to } d\Phi' = \frac{2}{r_1^2}x_1 dx_1 \times \frac{x_1^2}{r_1^2} \times i_a = \frac{2x_1^3 dx_1 i_a}{r_1^4}$$

Hence
$$L_{c_2} = \frac{2}{r_1^4}\int_0^{r_1} x_1^3 dx_1 = \frac{2}{r_1^4} \times \frac{r_1^4}{4} = \tfrac{1}{2}$$

Hence total inductance per cm due to the flux of conductor A is

$$L = \left(2\log_e\frac{D}{r_1} + \tfrac{1}{2}\right) \text{ abs. units}$$
$$= \text{effective inductance of one wire.}$$

Since the currents in the two conductors are in opposite directions, the total fluxes produced in each are added.

Hence total inductance per cm due to both conductors

$$= \left(4\log_e\frac{D}{r_1} + 1\right) \text{ abs. units.}$$

If the conductor has an inner hemp or other non-conducting core of radius r_4 the total inductance per cm due to both conductors is given by

$$L = \left[4\log_e\frac{D}{r_1} + \frac{r_1^2 - 3r_4^2}{(r_1^2 - r_4^2)} + \frac{4r_4^4}{(r_1^2 - r_4^2)^2}\log_e\frac{r_1}{r_4}\right] \text{abs. units.}$$

For a length l cm each expression is multiplied by l.

(2) For the second coefficient of self-induction with

which we are concerned the argument is as before, and for the lead system we therefore have :—

Total inductance per cm due to the double line

$$= L_s = \left[4 \log_e \frac{D}{r_3} + \frac{r_3^2 - 3r_2^2}{(r_3^2 - r_2^2)} + \frac{4r_2^2}{(r_3^2 - r_2^2)^2} \log_e \frac{r_3}{r_2}\right] \text{abs. units.}$$

As before, this expression is multiplied by l for a length l cm, and its reactance

$$x_s = \omega L_s = 2\pi f L_s.$$

(3) The mutual inductance between the copper and lead circuits will be denoted by M.

The field at a point Q distant x from the centre of A is $2i_a/x$. If $d\Phi_1$ is the flux traversing an element comprised between the cylinders of radii x and $(x + dx)$, then $d\Phi_1 = (2i_a/x)dx$ per cm length.

The current linked by $d\Phi_1 = i_s\left(\frac{x^2 - r_2^2}{r_3^2 - r_2^2}\right)$

Linkages due to $d\Phi_1 = \frac{2i_a}{x} \times i_s \times \left(\frac{x^2 - r_2^2}{r_3^2 - r_2^2}\right)dx$

$$M_1 = \frac{2}{(r_3^2 - r_2^2)} \int_{r_2}^{r_3} \frac{x^2 - r_2^2}{x} dx$$

$$= 1 - \frac{2r_2^2}{(r_3^2 - r_2^2)} \log_e \frac{r_3}{r_2}$$

The field at a point outside the lead sheath of A and distant x from the centre of A is $2i_a/x$.

Flux $d\Phi = (2i_a/x)dx$ per cm length. This flux links the whole of the lead sheath current i_s.

$$M_2 = \int_{r_3}^{D} \frac{2}{x} dx$$

$$= 2 \log_e \frac{D}{r_3}$$

The total inductance per cm due to flux of conductor A is

$$\left[1 - \frac{2r_2^2}{(r_3^2 - r_2^2)}\left(\log_e \frac{r_3}{r_2}\right) + 2 \log_e \frac{D}{r_3}\right] \text{abs. units}$$

Mutual inductance per cm due to both cables

$$= M = \left[2 - \frac{4r_2^2}{(r_3^2 - r_2^2)} \log_e \frac{r_3}{r_2} + 4 \log_e \frac{D}{r_3}\right] \text{abs. units.}$$

It will be assumed that the lead sheath is a complete circuit, the ends being bonded across, and the following symbols will be taken to refer to the long rectangular loop so formed.

I = current flowing in the conductors.
R = ohmic resistance of the copper circuit per cm length of the loop (go and return).
i_s = current flowing in the lead sheath.
l = length of each conductor.
D = distance between the axes of the two cables.
r_s = ohmic resistance of the lead-sheath circuit per cm length of the loop.
V = P.D. applied to the copper circuit.
$\omega = 2\pi f$, where f = frequency in periods per second.
M = coefficient of mutual induction between the copper and lead circuits per cm length of loop.
L = coefficient of self-induction between the copper (or primary) circuit per cm length of loop
= total interlinkage of the copper circuit with the flux produced by unit current in the cores.
L_s = coefficient of self-induction of the lead-sheath circuit per cm length of loop.
S = coefficient of stray induction of the copper circuits per cm length of loop
= total interlinkage of the copper circuit with the copper stray flux produced by unit current in the cores.
S_s = coefficient of stray induction of the lead-sheath circuit per cm length of loop.

Then $L = S + M$ for the copper circuit per cm length of loop and $L_s = S_s + M$ for the lead circuit per cm length of loop, i.e. $M^2 = (L - S)(L_s - S_s)$.

Then for the very long rectangular loop the following equations apply :—

$$V = IR + L\frac{dI}{dt} + M\frac{di_s}{dt} \quad . \quad . \quad . \quad . \quad (1)$$

$$0 = i_s r_s + L_s\frac{di_s}{dt} + M\frac{dI}{dt} \quad . \quad . \quad . \quad (2)$$

Assuming V to vary sinusoidally, Equations (1) and (2) may be solved to give I and i_s, the solution involving differential equations of the second degree. The mathematical problem is well known and the method of solution is briefly as follows*: With the currents I and i_s assumed to differ in phase by θ and following the equations $I = \hat{I} \sin \omega t$ and $i_s = \hat{i}_s \sin (\omega t + \theta)$, the useful results are :—

$$\tan \theta = \frac{r_s}{\omega L_s}; \quad \sin \theta = \frac{r_s}{\sqrt{(r_s^2 + \omega^2 L_s^2)}} \quad . \quad (3)$$

$$\hat{i}_s = -\frac{\omega M \hat{I}}{\sqrt{(r_s^2 + \omega^2 L_s^2)}} \quad . \quad . \quad . \quad . \quad (4)$$

$$V = \hat{I}\sqrt{\left[\left(R + \frac{\omega^2 M^2 r_s}{(r_s^2 + \omega^2 L_s^2)}\right)^2 + \omega^2\left(L - \frac{\omega^2 M^2 L_s}{r_s^2 + \omega^2 L_s^2}\right)^2\right]} \sin (\omega t + \Phi) \quad . \quad (5)$$

$$\text{where} \quad \tan \Phi = \frac{\omega[L - (\omega^2 M^2 L_s)/(r_s^2 + \omega^2 L_s^2)]}{[R + (\omega^2 M^2 r_s)/(r_s^2 + \omega^2 L_s)]} \quad . \quad (6)$$

The current I in the conductor lags behind the voltage by an angle Φ.

Apparent resistance of the copper circuit

$$= R + \frac{\omega^2 M^2 r_s}{r_s^2 + \omega^2 L_s^2} \quad . \quad . \quad . \quad . \quad (7)$$

* S. G. Starling: "Electricity and Magnetism," 4th edn., p. 350.

Apparent inductance of the copper circuit

$$= L - \frac{\omega^2 M^2 L_s}{r_s^2 + \omega^2 L_s^2} \quad . \quad . \quad . \quad . \quad (8)$$

From these equations it is seen that eddy currents in the lead sheath can be regarded as being equivalent to an increase in resistance and a decrease in inductance of the cores, resulting in increased losses. Equations (7) and (8) indicate that the magnitude of the eddy-current effects depends upon (and increases with) the frequency of the current in the conductors and upon the dimensions of the latter.

Vector Diagram for the E.M.F.'s Arising in a Single-Phase Cable Circuit with Lead Sheaths Bonded.

Equations (1) and (2) can be combined in the vector diagram given in Fig. 12, where the vectors OA, AB,

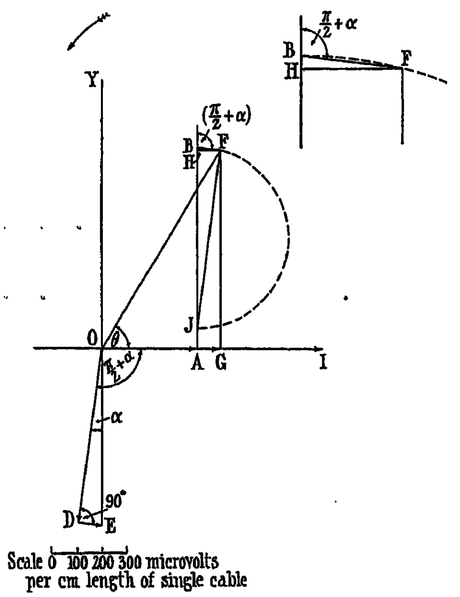

Fig. 12.—Vector diagram for the E.M.F.'s arising in a single-phase 0·5 sq. in. cable circuit with axes 10 cm apart and lead sheaths bonded.

BF, and the vectors OD, DE, OE, correspond to (1) and (2) respectively.*

Let OI be reference vector,

OA $= R\hat{I}$ in phase with the copper current,

AB $= \omega L\hat{I}$ (90° ahead of OA),

OD $= r_s\hat{\imath}_s$ in phase with the lead-sheath current,

$$\hat{\imath}_s = -\frac{\omega M\hat{I}}{\sqrt{(r_s^2 + \omega^2 L_s^2)}}$$

$\angle$ AOD $= (\frac{1}{2}\pi + \alpha)$

DE $= \omega L_s\hat{\imath}_s$, 90° ahead of OD

where α is given by $\tan \alpha = \dfrac{\omega L_s}{r_s}$

* S. G. Starling, *loc. cit.*, p. 361.

OE = vector sum of OD and DE

= E.M.F. induced in the lead due to variation of copper current

$= M\dfrac{dI}{dt}$ (parallel to OY)

$= \omega M\hat{I}$

BF = E.M.F. induced in the copper circuit due to variation of lead-sheath current

$= \omega M\hat{\imath}_s$ (parallel to DE)

$$= \frac{\omega^2 M^2 \hat{I}}{\sqrt{(r_s^2 + \omega^2 L_s^2)}}$$

OF = the resultant of (OA, AB and BF)

= applied P.D. to copper circuit.

Effective Resistance and Effective Reactance of the Copper Circuit.

By suitably altering the scale of the diagram we can make the vectors represent ohms instead of volts, as an air-core circuit is being considered.

Drawing FG perpendicular to OI and FH perpendicular to AB we have the effective resistance of copper circuit represented by OG $= R_1\hat{I}$, say,

$$\text{OG} = \text{OA} + \text{AG} = \text{OA} + \text{HF}$$
$$= \text{OA} + \text{BF} \sin(\tfrac{1}{2}\pi - \alpha) = \text{OA} + \text{BF} \cos \alpha$$

Therefore $\text{OG} = \hat{I}R + \dfrac{\omega^2 M^2 \hat{I}}{\sqrt{(r_s^2 + \omega^2 L_s^2)}} \cos \alpha$

Effective resistance of copper circuit

$$= R_1 = R + \frac{\omega^2 M^2 \cos \alpha}{\sqrt{(r_s^2 + \omega^2 L_s^2)}}$$

but $\cos \alpha = \dfrac{r_s}{\sqrt{(r_s^2 + \omega^2 L_s^2)}}$

therefore $R_1 = R + \dfrac{\omega^2 M^2 r_s}{r_s^2 + \omega^2 L_s^2}$

The effective reactance of the copper circuit is represented by

FG $= \omega L_1 \hat{I}$ (say)

FG = AB − BH = AB − BF sin α

$$= \omega L\hat{I} - \frac{\omega^2 M^2 \hat{I}}{\sqrt{(r_s^2 + \omega^2 L_s^2)}} \times \frac{\omega L_s}{\sqrt{(r_s^2 + \omega^2 L_s^2)}}$$

$$= \omega L\hat{I} - \frac{\omega^3 M^2 L_s \hat{I}}{r_s + \omega^2 L_s^2}$$

Therefore $\omega L_1 = \omega L - \omega L_s\left(\dfrac{\omega^2 M^2}{r_s^2 + \omega^2 L_s^2}\right)$

or $X_1 = X - x_s\left(\dfrac{\omega^2 M^2}{r_s^2 + \omega^2 L_s^2}\right)$

The angle FOA $=\theta$ is the angle by which the copper current lags behind the applied P.D. to the core. Thus with the lead-sheath circuit closed and consequently a current of i_s circulating in the lead, the effect, as

already shown, is to cause an apparent increase in the resistance and an apparent decrease in the self-inductance of the copper circuit. In every case a lead-sheath current results in increased power being absorbed by the cable, either by increasing the core current or by altering the phase of the copper current.

OF represents the impedance when the lead circuit is completed, and OB the impedance when the lead circuit is open, showing that the impedance in the first case may be greater than in the second case.

If FJ is drawn perpendicular to BF, i.e. $\angle$ BFJ $= \frac{1}{2}\pi$, we have

$$\begin{aligned} \text{BJ} &= \frac{\text{BF}}{\cos(\frac{1}{2}\pi - \alpha)} \\ &= \frac{\omega^2 M^2 \hat{I}}{\sin\alpha\sqrt{(r_s^2 + \omega^2 L_s^2)}} \\ &= \frac{\omega^2 M^2 \hat{I}}{\omega L_s} \end{aligned}$$

$$\begin{aligned} \text{AJ} &= \text{AB} - \text{BJ} \\ &= \omega L\hat{I} - \frac{\omega^2 M^2 \hat{I}}{\omega L_s} \\ &= \frac{\omega\hat{I}}{L_s}(LL_s - M^2) \end{aligned}$$

Now M^2 cannot be greater than LL_s, since it is impossible for the core and sheath to enclose the whole of the magnetic flux. Hence $1 - [M^2/(LL_s)]$ must have a positive value.

The Case when the Lead Sheath is Open-Circuited.

It is of interest to consider the case where the lead sheath does not form a complete circuit.

We have $i_s = 0$, $r_s = \infty$, $\alpha = 0$.

The vector diagram becomes as shown in Fig. 13.

$$\begin{aligned} \text{OA} &= R\hat{I} \\ \text{AB} &= \omega L\hat{I} \\ \text{OE} &= \omega M\hat{I} \end{aligned}$$

E.M.F. in the lead sheath = OE = $\omega M\hat{I}$.

If the copper resistance (OA) is small, then OE is nearly 180° out of phase with the applied E.M.F. to copper (OF).

$\hat{e}_s = \omega M\hat{I}$, and this is the voltage induced in the lead when the sheath is insulated.

Impedance is represented by OB.

The difference between the open-circuit and closed-circuit conditions may be better realized by imagining that the circuit is completed through a gradually diminishing resistance.

As the resistance of the lead circuit diminishes from infinity (the diagram being of the form shown in Fig. 12), the point F moves over the arc of a circle of diameter BJ in the direction BFJ. Additional power is absorbed by the cable in order to maintain the same current in the core, and, in the limit, the minimum value r_s is reached when the sheath is closed on itself.

Effect on the Permissible Current Loading.

Having determined an expression for the losses we proceed to determine the permissible current loading in the cable for a given temperature-rise. In any such case the procedure is on the assumption that we can express the loss of energy occurring in the sheath in the form I^2R_1, where R_1 represents the resistance by which the ohmic resistance of the core must be increased so that I^2R_1 is equivalent to the lead-sheath loss.

Thus if I = permissible current loading of core,
and R = direct-current resistance of core,
total losses W = copper losses W_c + lead-sheath losses W_s

$$\begin{aligned} W &= W_c + W_s \\ &= RI^2 + R_1 I^2 \\ &= I^2(R + R_1) \end{aligned}$$

Alternatively, we may take I_1 to be the conductor current which, flowing through the ohmic resistance

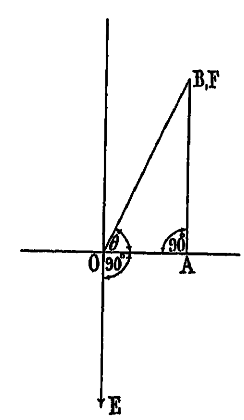

Fig. 13.

R of the copper system, gives rise to a loss equivalent to the lead-sheath loss.

Then, as before, $W = W_c + W_s$

therefore $\quad W = I^2R + I_1^2R = R(I^2 + I_1^2)$.

Then if I_e be the direct current which, flowing through the conductor, produces the same heating as is produced under alternating-current working, we have

$$I_e^2R = R(I^2 + I_1^2)$$

Therefore $\quad I_e^2 = I^2 + I_1^2.$

Now I_e, the intensity of direct current producing a given temperature-rise in the cable, is directly determinable when the conditions of laying are known. In the case of the tests described in the paper, curves are given which enable the value I_e to be read off directly. For cables laid under certain conditions the values of the current for a given temperature-rise of the core can be obtained from other sources.* I_1 is given by $W_s = I_1^2R$. Hence I is calculable.

* S. W. Melsom and H. C. Booth: *Journal I.E.E.*, 1911, vol. 47, p. 711; also S. W. Melsom and E. Fawssett: *Ibid.*, 1923, vol. 61, p. 517.

Returning to the first method where the ohmic resistance of the core is increased by an amount R_1 we have, from the preceding, the lead-sheath loss given by

$$W_s = i_s^2 r_s$$
$$= I^2 r_s\left(\frac{\omega^2 M^2}{r_s^2 + \omega^2 L_s^2}\right) = W_c\left(\frac{r_s}{R}\right)\left(\frac{\omega^2 M^2}{r_s^2 + \omega^2 L_s^2}\right)$$

Also $\quad W_s = I^2 R_1$ and $W_c = I^2 R$.

Therefore $\quad \dfrac{W_s}{W_c} = \dfrac{R_1}{R} = \dfrac{r_s}{R}\left(\dfrac{\omega^2 M^2}{r_s^2 + \omega^2 L_s^2}\right)$

where R = direct-current resistance of the core,
R_1 = resistance by which the square of the permissible current is multiplied to give the lead-sheath loss,
$(R + R_1)$ = resistance by which the square of the permissible current is multiplied to give the total losses under alternating-current working,
and I = permissible current loading under alternating-current working.

This means that lead losses may be expressed in terms of conductor loss and, therefore, regarded as a decrease in the copper cross-section, the loading being correspondingly reduced.

Let $\quad R_f = R + R_1$

If a_f, a and a_1 are the cross-sections corresponding to the resistances R_f, R and R_1

then $\quad \dfrac{1}{a_f} = \dfrac{1}{a} + \dfrac{1}{a_1}$

where a_f is the section of a fictitious conductor carrying the permissible current I in which the direct-current loss is equal to the loss occurring in the actual cable of section a

$$\frac{a_f}{a} = \frac{R}{R + R_1}$$

Proceeding on the assumption that the total heating occurs wholly in the core, we can determine the permissible loading when alternating current is employed.

The relation between the current I in a cable of cross-section a, when only conductor heating is considered, is given by

$$I = f(a)$$

Hence if I = actual current loading, and
I_e = theoretical current loading

then $\quad \dfrac{I}{I_e} = f\left[\dfrac{a_f}{a}\right] = f\left[\dfrac{R}{R + R_1}\right]$

This may also be expressed graphically as in Fig. 14, where curve 1 is given by $I = f(a)$

Now $\quad \dfrac{W_s}{W_c} = \dfrac{R_1}{R} = \dfrac{a}{a_f} - 1 = \dfrac{a}{a_1}$

Hence $\quad a_1 = \dfrac{W_c}{W_s} \times a.$

In the figure, AC is given by $(W_c/W_s) \times$ AB, since B is a point on the curve $I = f(a)$, and AC represents the copper cross-section across which the square of the current OA flows to produce the lead-sheath losses. A series of points can thus be obtained from experiment or calculation, and curve 2 drawn through them will satisfy the equation

$$a_1 = \frac{W_c}{W_s} \times a.$$

To complete the figure we join OC, draw BM perpendicular to the horizontal axis, and join AM cutting OC in P.

Then the ordinate RQ gives the permissible current loading with alternating current.

The section represented by OQ gives with an alternating-current loading (represented by RQ) the same

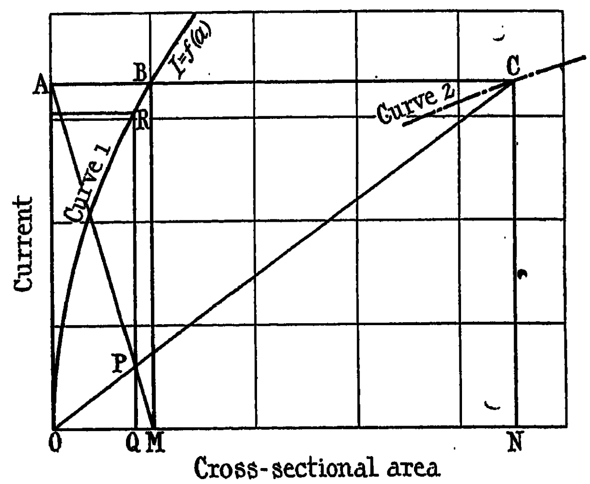

FIG. 14.—Construction for obtaining the permissible loading of a cable circuit on the assumption that the total heating occurs wholly in the conductor.

loss of energy as the section represented by OM gives with a direct-current loading represented by BM.

$$OQ = a_f$$
$$OM = a$$
$$ON = a_1$$

and $\quad \dfrac{1}{a_f} = \dfrac{1}{a} + \dfrac{1}{a_1}$

A similar figure has been given by Soleri* in connection with the dielectric losses in high-tension cables.

The calculated value of the ratio R_{eff}/R is greater than the measured value in the case of the large cable (0·5 sq. in.) working at its normal rating, but the formula is in good agreement with experimental determination for the cables of 0·3 sq. in. and 0·1 sq. in. cross-section.

The maximum difference observed over the range of cables tested was about 4 per cent of the current loading, which is probably near enough for practical purposes.

The differences between actual and calculated values are due partly to small differences of temperature.

* Bibliography, item (6).

Further, in the theory a number of assumptions are made in order that the mathematics may become manageable, but it is evident that some of these do not completely fit the facts. For example, the theory assumes uniform current distribution, whereas the latter is affected by the presence of the return conductor. In this instance, however, formulæ are avilable for estimating this effect, and, for further particulars, "Theorie der Wechselströme" by J. L. La Cour and O. S. Bragstad should be consulted. Also, in the calculation of the coefficients of induction the effect of end-connections is neglected.

The impedance and power were not checked experimentally, but the theory shows that the resistance factor is the important one in the expression for impedance. As pointed out by Atkinson,* it is possible for the impedance of the cable to be greater when the lead is short-circuited than when it is open-circuited.

In considering the experimental work it is important, in order to obtain results of any value from a theoretical treatment, to know the actual values of the resistances of the copper and lead per unit length, more especially the lead. These "constants" should be obtained by measurements on the actual cable, for they are important factors in the theory and it is of little use to assume a resistivity for lead and work from the dimensions to get the losses. Small variations in r_s affect the calculated losses to an appreciable amount. These precautions will be more important when dealing with the larger sizes of single-conductor cable with small spacings, for then the theory is likely to depart still further from practice, owing to the difficulty of accounting for the complex proximity effect.

The fact that even with the largest size of cable tested no measurable difference could be detected between the heating with direct current and with alternating current, and the lead sheaths being open-circuited, indicates that under these conditions the eddy-current effects (skin effect) in sheath and in conductor are negligible. With still larger sizes of cable, however, the skin effect would become appreciable.

* Bibliography, item (4).

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DISCUSSION BEFORE THE NORTH-EASTERN CENTRE, AT NEWCASTLE, 24 NOVEMBER, 1924, ON THE ABOVE PAPER AND ON A PAPER * BY MESSRS. MELSOM AND BOOTH.

Mr. E. Fawssett: The paper by Messrs. Melsom and Beer is a very good example of a carefully controlled series of experiments the results of which are compared with theory. I wish, however, that the authors had carried their investigations to greater separations—at least on one size of cable to obtain the characteristic—and had also employed up to at least 1·0 sq. in. cables, as the additional sheath losses rise very rapidly with the size of cable used. The theoretical law of sheath losses versus separation in a single-phase system was shown † by Prof. Cramp and Miss Calderwood to depend on a logarithmic term $\log_{10}[(1 - K^2)/K]$, K being the ratio of the cable radius to the axial separation, and varying from 0·23 with the cables nearly touching to 36 (theoretically) when the return cable is at a nearly infinite distance away, or, say, about 1 to 150. This ultimate figure is, of course, impossible because of the bond resistance then necessary. The curve drawn for the ratio a.c./d.c. loading from this formula, after providing for the proximity effect, comes well below the authors' experimental results at moderate separations, and this is a further reason why they should have shown the effect of separation over a wider range, seeing that it is rapidly increasing at the point where they left off. I consider that the authors were quite right to limit their investigations to a "continuously earthed" system, as this is the usual and also the severest case. While the method of measurement adopted is justified in their case for this particular investigation, it is not one ordinarily capable of great accuracy and requires very specially close control of the current and of the room temperature: at a temperature-rise of 35 deg. C. this ought to be held to within ½ deg. C., which is, I think, scarcely possible. I have not been able to repeat results by this method with such accuracy as would permit me to assert that a 0·5 sq. in. single cable will carry exactly the same current with direct current as with alternating current at 50 periods per sec., and considering the additional losses that there must be in the latter case (sheath eddy currents 1 per cent and skin effect about 1 per cent in terms of copper loss) it would not appear to be rigidly true. More especially does it seem remarkable

* "The Current-Carrying Capacity of Solid Bare Copper and Aluminium Conductors," *Journal I.E.E.*, 1924, vol. 62, p. 909.

† "The Use of Single-Core Sheathed Cables for Alternating Currents," *ibid.*, 1923, vol. 61, p. 477.

that this method could detect no difference between direct and alternating current for a pair of 0·5 sq. in. cables with sheaths not bonded but with iron interposed, when the induced sheath voltage is very much higher than normal and there must be some losses in the iron preventing it having the same cooling effect as on direct current. The equation $I_1^2R_1 = I^2R$ given on page 191 would hold as stated for equal heating in the two cases, but I submit that for a given core temperature-rise the heat-flow conditions with direct and alternating current respectively are very far from equal. With the latter a large percentage of the total watts are expended directly in the sheath and therefore only elevate the core temperature by approximately 75 per cent of what they would if they were expended in the core. Consequently the increment over the copper loss should be increased by 1/0·75 or 33 per cent in order that the resulting effective resistance figure may really represent the watts that have to be supplied. This does not in any way vitiate the experimental results or the conclusions to be drawn from them, provided it is made quite clear that R_1 is the a.c. resistance for thermal considerations only. Seeing that the theory of mutual heating has been worked out, I scarcely think that in Table 1 *et seq.* the term *theoretical* current-loading should be employed for a value which it is known must be wrong, and I would suggest substituting

$$\frac{\text{Pair d.c. loading*}}{\text{Single d.c. loading}}$$

In Fig. 4, curve F seems to agree closely with Prof. Cramp's and Miss Calderwood's figures, curve B showing that the practical result is substantially better. This divergence increases with the size of the cable and if the figures for a 1 sq. in. cable showed the same tendency exaggerated they would be very reassuring. It should be emphasized that Fig. 5, showing the increment of apparent resistance, is applicable to core heating only, since the real effective electrical resistance is considerably higher, the figures to compare with the last column of Table 3 being 1·112, 1·164, 1·39 and 1·557, this last showing a 10 per cent increase over the figure 1·417 in the table. If "proximity effect" curves be drawn from Tables 1, 8 and 10, it is remarkable that the 0·5 sq. in. value starts, when sheaths are in contact, between the values for the 0·3 sq. in. and 0·1 sq. in. sizes. Can the authors account for this? I should like to see an additional figure, similar to Fig. 8, for the case of Table 12. Curve E in Fig. 8 corresponds to curve A for the iron-free condition, but it cannot be combined with C, as the proximity effect with iron interposed is quite different, and a new curve F is required, the resultant of which with E, say G, would then be comparable with D in Fig. 8, giving a different separation, I think, for the maximum loading. There seem to be serious discrepancies in Tables 13 and 14 [since revised for the *Journal*]. The authors state (in the advance copies of the paper) that the relation between the current I in a cable of cross-section a when only the conductor heating is considered is given by $a = KI^2$. If this means "for constant watt loss" I agree, but if, as the curve derived from it in Fig. 14 states, "permissible loading," i.e. constant temperature-rise, is meant, then the watt loss varies as the radius of the cable. Consequently, if the radius be doubled and the area therefore increased four times, the ratio of the squares of the two currents appears to be 1 to 8 for constant temperature-rise, whereas according to the quoted equation it should be 1 to 4. Perhaps I have misunderstood the authors' meaning, but as the construction in Fig. 14 depends on it I should like to hear their explanation. From results on single-core cables in the Report on the Heating of Buried Cables it would appear that, experimentally, $a = KI^{1\cdot5}$. The experimental results in the paper will certainly be of very great value indeed to all users of single-core cables.

* Since substituted in the paper as printed in the *Journal*.

Mr. H. Parry: The cooling-curve method of determining h described by Messrs. Melsom and Booth in their paper published in the November 1924 issue of the *Journal* is very neat, and it is very satisfactory to know that the heat loss can be determined from such simple equations. The method has the disadvantage that the specific heat must be known; this appears to be a variable for copper, as values given in the Smithsonian tables covering the temperature interval 25 deg. C. to 100 deg. C. are 0·0917 to 0·0942 respectively. For busbar purposes the results obtained with dull black paint are chiefly of theoretical interest, as the bars are usually either not painted or painted with the colours red, white and blue for marking polarity, the paints having a glossy surface. I think that it would be of great practical value if the authors would give figures for h under these conditions. The "proximity effect" tests should have included tests with the spacing between the bars equal to the bar thickness, for in multiple-bar busbars this seems to be the usual practice. I think it is worth noting that busbars have not only their own losses to radiate but have to carry away most of the heat from ammeter shunts and such-like apparatus, and allowance should be made for this. I have compared the values for h given in the paper with those given for lead cable sheaths of 1 in. and 1¾ in. diameter in the *Journal* (1923, vol. 61, p. 571), where the average figures are 0·0007 (bright) and 0·0011 (black) at a temperature of 30° C. These values are much higher than those given by the authors. Do they consider that this is due to the lower temperature or to the nature of the surface? I think that the brackets in Equation (3), page 910 (vol. 62), should be deleted.

Mr. T. Carter: With reference to Messrs. Melsom and Booth's paper, it would appear that the regulations specifying that busbars shall be painted with colours to indicate their polarity or their phase relation may have the effect, since bright enamels are often used, of seriously reducing the carrying capacity of the bars, and further comment by the authors on this point is very desirable. The paper states a definite figure for the reduction in carrying capacity due to the placing of two bars near each other with a distance between them equal to their breadth; it is important to know what the effect is of placing bars near each other with a distance between them approximately equal to their

thickness, this being the arrangement commonly met with in bars with interleaved joints, when the parts between the joints are spaced out from each other by the thickness of the interleaved strips. What, for example, would be the effect of using 8 pieces 3 in. × $\frac{1}{8}$ in., spaced $\frac{1}{8}$ in. apart, in place of one solid piece 3 in. × 1 in.?

Messrs. S. W. Melsom and **W. E. Beer** (*in reply*): The separation of the cables was not carried much beyond 12 inches, as this was considered to cover the practical range of spacings. The method of measurement employed is capable of a good degree of accuracy, as pointed out in the paper. The arrangements for steady temperature require special consideration, but are in no way impossible. In the case referred to at the top of page 195 in which no difference was observed between the heating with alternating current and with direct current for a pair of 0·5 sq. in. cables the axes of which were 12·5 inches apart, this result would be expected from theoretical considerations and is in agreement with the observations of other experimenters. Doubtless there are small additional losses with open-circuited sheaths, for the reasons given by Mr. Fawssett, but they are too small to be detected. Such detection would require measurements having an overall accuracy lying within $\frac{1}{2}$ of 1 per cent.

We agree with Mr. Fawssett in the matter of the heat-flow conditions with alternating- and direct-current loadings, and also on his observations with respect to effective resistance. The figures given for R_1 and $\frac{R_{eff.}}{R}$ all refer to a thermal basis, and the values of effective resistance to alternating current on a watt basis, as usually understood, would be greater than those given, owing to the losses in the sheath. These remarks apply also to Fig. 5. The substitution of

$$\frac{\text{pair d.c. loading}}{\text{single d.c. loading}} \text{ for } \frac{\text{actual d.c. loading}}{\text{theoretical current loading}}$$

in Tables 1, 8, and 10 has been made in accordance with Mr. Fawssett's suggestion.

Referring to Fig. 4 wherein the practical result (curve B) is substantially better than the theoretical result (curve F), this is all to the good, but it should be noted that the mutual heating effect is of great importance at the usual spacings, and considerably modifies the permissible loading, taking into account only the sheath losses. In practice the sheath inductive effects, for given dimensions of conductors and for a given spacing, would be governed largely by the bonding resistance introduced, and, further, there is the damping effect of the eddy currents in the lead sheaths, which would introduce a divergence between measured and calculated values. As regards the starting points of the proximity or mutual heating-effect curves, the results given were those obtained by experiment and the difference between the 0·3 and 0·5 sq. in. cable circuits is, in any case, not large.

Mr. Fawssett refers to Fig. 8, in which the curves for a 0·1 sq. in. cable system are plotted. As he points out, curves E and A are comparable, and they show that the presence of iron at the lowest spacing (1·23 in.) decreases the permissible current-loading by about 7 per cent. The mutual heating effect is additional to this and, referred to the case of a single cable in air, is 97·3 per cent at 1·23 in. spacing, 99·8 per cent at 3·2 in. spacing, and 100 per cent at 7·25 in. and greater spacings. Thus the actual loading at 1·23 in. spacing with iron interposed will be reduced to 89·3 per cent of the loading of a single cable in air. The latter has been taken as standard, for this is the value given for all sizes of cables in the Report on the Heating of Buried Cables, whereas the rating of a single cable laid against an iron girder (which might have been used) has no general meaning.

We have to thank Mr. Fawssett for drawing attention to the discrepancies that appeared in Tables 13 and 14 in the advance copies of the paper; these have been revised for the *Journal.*

Mr. Fawssett has also drawn attention to an expression $a = kI^2$ which appeared in the advance copies of the paper. It arises from the procedure of expressing the sheath loss in terms of an increased core loss, i.e. the total energy loss is compared with the loss arising in the conductor only of a cable the section of which is less than the actual cross-section. In the paper the changes in resistance and cross-section are denoted by R_1 and a_1 respectively. For single-core cables $I^2R = k\theta$, where k is a constant for given conditions of laying and given dimensions of cable, and θ is the temperature-rise of the core above the medium in which the cable is disposed. Then for cables having the same overall lead diameter and the same temperature-rise, $k\theta$ is constant, and small changes in I and R will be given by

$$\frac{I}{I_e} = \sqrt{\left(\frac{R}{R + R_1}\right)} = \sqrt{\left(\frac{a_f}{a}\right)}$$

If, however, the extreme case is taken (similar to Mr. Fawssett's example) where the copper area is increased four times, with consequently large changes in the emissivity constant, then the relation $I = f(a)$ should be employed, the function to be determined from the experimental results in the paper, or it may be deduced, as Mr. Fawssett has done, from the recent Report on the Heating of Buried Cables. The last relation is generally true and, to meet Mr. Fawssett's point, has been substituted in the paper. This will, however, make no difference to the method of construction shown in Fig. 14, which is simply a geometrical construction corresponding to the expression

$$a_f = \frac{aa_1}{a + a_1}.$$

Messrs. S. W. Melsom and **H. C. Booth** (*in reply*): Mr. Parry draws attention to an apparent discrepancy between the values of the heat-emissivity constant given in the Buried Cables Report and those deduced from the formula. It should be pointed out, in connection with the values of h which appear in the earlier Report, that Newton's law of cooling was assumed; but as the results now given indicate, the assumption that the rate of cooling is proportional to the 5/4 power of the temperature excess is more nearly correct and has been used in deducing the values of h. If this assumption be followed, the values of h derived from the data quoted in the *Journal* will be found to be closely in agreement with those deduced from Equation (5).

It will also be noticed that the ratio of the emissivities of bright to black surfaces, as derived from the mean of all the results given in the earlier Report, namely 0·00070 and 0·00107, or 1/153, is almost identical with that now deduced, namely 1/154. In deducing the values of h the specific heat of copper was taken as 0·094, which is a fair mean of the specific heat for the range of temperature over which the emissivity was measured, and is in good agreement with the latest determinations.

In reply to Mr. Carter, the effect on the emissivity constant when bars are separated by a distance equal to their thickness, which occurs when a number of strips are interleaved, was not considered, though it is hoped to investigate this problem at a later date. Meanwhile it would be safest to assume that under these conditions the emissivity is approximately equal to that of a solid bar having the same girth. Thus in the case quoted by Mr. Carter the girth of the eight pieces, 3 in. × $\frac{1}{8}$ in. would be $2(3 + 1\frac{7}{8}) = 9\frac{3}{4}$ in. This leaves out of account the heat emission from the inner surfaces of the interleaved strips, but on the other hand it will compensate for the greater temperature-rise experienced by the centre strips as compared with the outer ones. It is probable that where the strips are painted with bright enamels the actual colours have little effect, and the emissivity from surfaces so painted will be very nearly the same as that from surfaces painted a glossy black, which was found to be about 12 per cent higher than that from bright metallic surfaces.

THE LOAD CHARACTERISTIC OF A DYNAMO GIVING CONSTANT CURRENT OVER A LARGE RANGE OF SPEED.*

By J. C. PRESCOTT, M.Eng., Associate Member.

(*Paper first received* 1*st August, and in final form* 22*nd October*, 1924.)

SUMMARY.

A graphical method of predicting the characteristics of a constant-current dynamo, such as the Rosenberg † or Brolt,‡ has been developed and, in the Appendix, the formula derived by the late Dr. Kapp § has been extended to determine the maximum current flowing in the short-circuited paths of the armature, and the steady value of the load current. It is also shown that the maximum value of the short-circuit current occurs when the load current reaches half its final value.

Tests carried out in the Laboratories of Applied Electricity of the University of Liverpool on a non-salient-pole machine are cited to show that the constant-current characteristic of the Rosenberg dynamo may be attained without the use of slotted or salient poles.

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* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† *Electrician*, 1905, vol. 55, p. 297; also *Elektrotechniche Zeitschrift*, 1905, vol. 26, p. 393.

‡ *Journal I.E.E.*, 1914, vol. 52, p. 107.

§ G. KAPP: "Principles of Electrical Engineering," vol. 2, p. 85.

INTRODUCTION.

The type of dynamo dealt with in this paper is designed for train and automobile lighting and will supply an almost constant current * to a load of constant resistance over a large range of speed, while the polarity of the load brushes is independent of the direction of rotation. When, as is usually the case, a battery is used, floating on the line, arrangements must be made to prevent the battery from being short-circuited when the generator speed is very low and the voltage, therefore, below the normal; an aluminium cell used as a valve is generally placed in series between the armature and the battery. The action of the generator (Rosenberg type) is as follows:—

The shunt field (see Fig. 1) produces in the armature an E.M.F. between the brushes "a" and "b." These brushes being short-circuited, a current passes in the armature conductors and gives rise to a cross field in the line AB at right angles to the line of the load brushes CD. A voltage therefore appears between "c" and "d" which is, for any given speed, proportional to the cross flux due to the short-circuit current in the armature. The load current in turn produces a flux in the line CD, in a direction opposite to that of the main field. At any given speed the short-circuit current must be proportional to the difference between the flux due to the current in the main field winding and that due to the load current in the armature conductors.

* A Rosenberg dynamo may be designed to give a current variation of 12 per cent between speeds of 800 and 2 400 r.p.m. when supplying a load of constant resistance.

Thus the increase in load current which occurs with an increase in speed in an ordinary dynamo, when working on a load of constant resistance, is reduced in the machine under consideration by an automatic weakening of the main field.

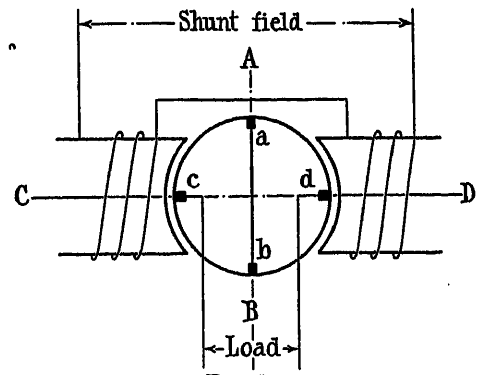

FIG. 1.

GRAPHICAL PREDETERMINATION OF CHARACTERISTICS.

The "speed/load current," and the "speed/short-circuit current" curves of the Rosenberg machine may be determined graphically if the field and armature saturation curves are known for some given speed, it being assumed that the armature resistance is R_a, the total short-circuit resistance R_s, and the load resistance R_l, the total turns on the field t, and the total armature turns T.

The method of predetermination is as follows :—

(1) The curves connecting field current and speed are plotted for various constant values of the short-circuit current.

(2) The straight lines connecting load current and speed are plotted for the same constant values of the short-circuit current.

(3) The field currents in (1) are reduced to equivalent load currents and the curves thus obtained plotted together with the lines from (2), on the axes of speed and load current. The points of intersection of the line and the curve thus obtained for any given value of the short-circuit current give two * points on the load-current/speed curve, while from the speeds corresponding to these intersections and the value of the short-circuit current on whose curve the intersections occur, the short-circuit-current/speed curve may be obtained.

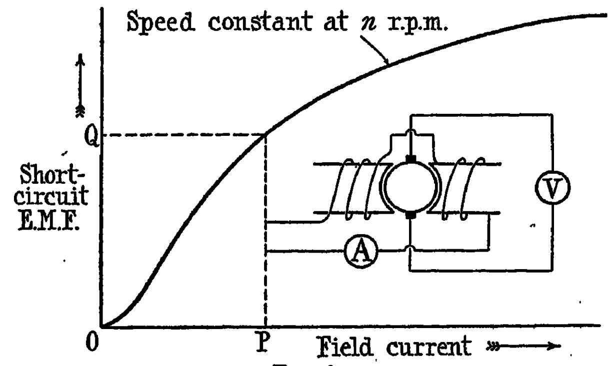

FIG. 2.

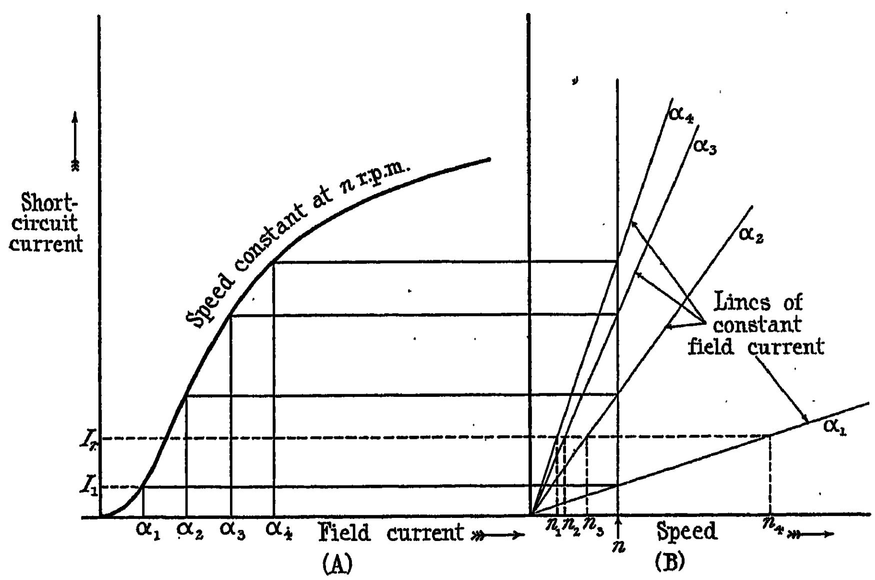

FIG. 3.

(1) *Field current and speed.*—The field saturation curve will give the relation between the field current and the voltage across the short-circuit brushes (the short-circuiting connection being removed). Let this curve represent the conditions at a speed of n r.p.m. (see Fig. 2). At any given field current OP, the short-circuit brush voltage is OQ at speed n, and will be (n'/n)OQ at speed n'. The resistance of the path of the short-circuit current being R_s, the curve may be made to represent the relation between speed and

* Except in the unique case where the curve is tangential.

short-circuit current if the ordinates are divided by R_s. This curve is shown in Fig. 3 (A). A series of straight

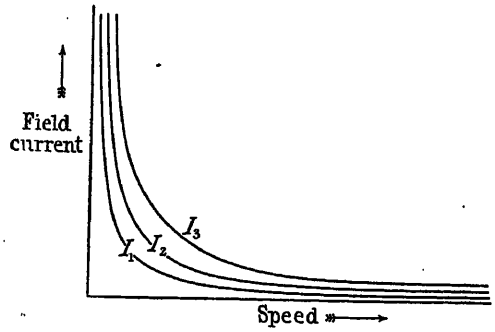

FIG. 4.—Curves of constant short-circuit current.

lines may therefore be drawn on the axes of speed and short-circuit current, each line representing some definite field-current [see Fig. 3 (A)].

constant short-circuit currents I'_1, I'_2, I'_3, etc., I'_1, I'_2, I'_3, etc., being chosen so as to be numerically equal to I_1, I_2, I_3, etc., respectively in Fig. 4.

(3) *Conversion of field current to equivalent armature load current.*—Curves have now been obtained between speed and field current, and between speed and load current, for various constant values of the short-circuit current. These curves must be combined to give the load current/speed characteristic. It has already been pointed out that the armature demagnetizing ampere-turns produced by the load current directly oppose the field ampere-turns (which are constant), the paths of the two fluxes being, of course, identical (neglecting leakage). The ordinates of Fig. 4 should therefore be converted to represent equivalent load currents, since it is obvious that the short-circuit E.M.F. could have been produced by exciting the armature from the load brushes instead of from the field.

If t = field turns and T = armature turns, the

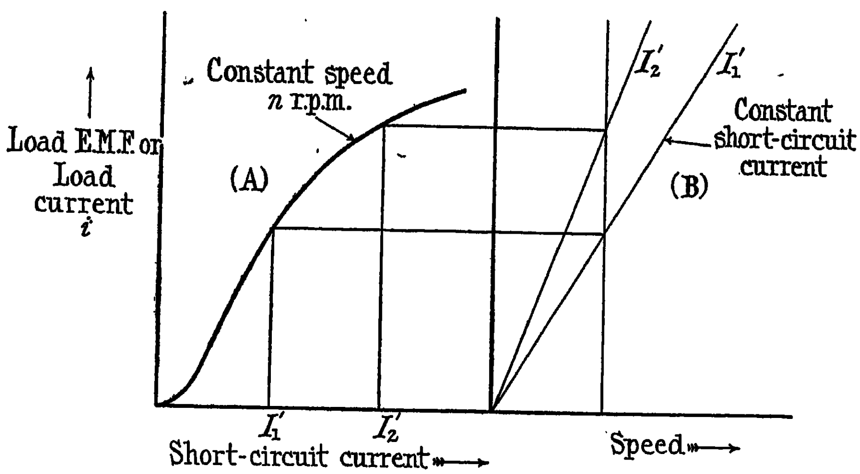

FIG. 5.

For a field current of a_1, the short-circuit current is I_1 for a speed of n, and is proportional to the speed if the field is constant. This gives the line a_1 in (B) which passes through the perpendicular erected at n at a height of I_1. The lines a_2, a_3, etc., are determined in the same way.

From these lines a family of curves may be obtained connecting field current and speed for various values of short-circuit current; for, taking any short-circuit current I_r, this current may be obtained by a_4 at speed n_1, or by a_3 at speed n_2, and so on. The curves are shown in Fig. 4.

(2) *Armature load current and speed.*—The armature saturation curve in Fig. 5 may now be considered. This curve gives the relation between the current in the short-circuit and the voltage on the load brushes. If this voltage be divided by $(R_a + R_l)$ the curve may be made to represent the relation between short-circuit current and load current. This curve is treated in the same way as that between short-circuit current and field current in order to obtain a pencil of lines representing the variation of load current with speed, for

conversion factor is ta/T, where a = number of parallel paths in the armature.

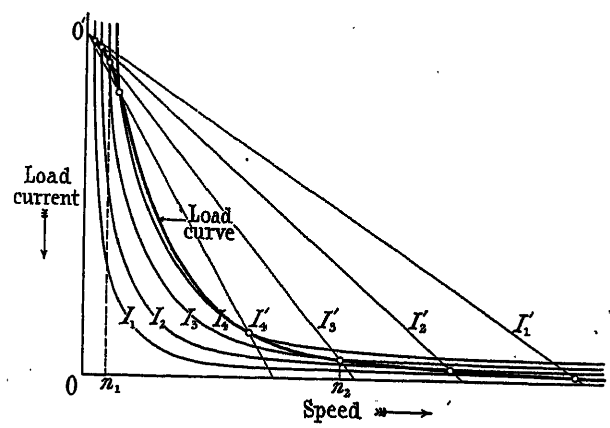

FIG. 6.

Let OO′ (Fig. 6) represent the normal field current in terms of the load current. When the machine is at

rest the resultant field in the line of the load brushes is OO′. As soon as the speed rises the load current flows, demagnetizing armature ampere-turns are intro-

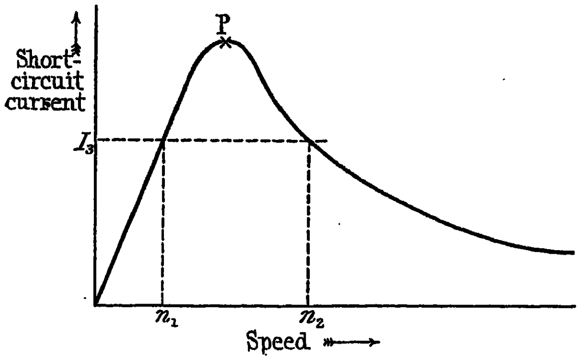

FIG. 7.

duced and the resultant field drops from O′ towards zero. The short-circuit lines [Fig. 5 (B)] must therefore

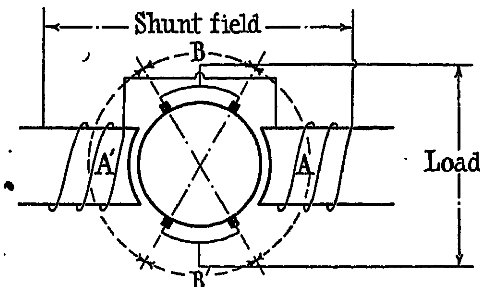

FIG. 8.

be drawn from O′ downwards, and points of stability occur where these lines cut the curves derived from Fig. 4. The load current/speed curve is obtained by join-

instance, the line I_3' cuts the curve I_3 at points corresponding to speeds n_1 and n_2. Thus if I_3 is plotted against speed, two points on the short-circuit-current/speed curve are obtained. This curve has the shape shown in Fig. 7. The value at P, being unique, corresponds to the short-circuit current whose line is tangential to the curve for that same current.

The voltage/speed curve can be calculated from the current curve, since the load resistance is constant.

Brolt machine.—The characteristic of the Brolt machine (see Fig. 8) may be obtained in a similar manner, though in this case the conductors producing the load voltage are contained in the arcs A, A′, and those carrying the short-circuit current in the arcs B, B′.

(2) TEST-RESULTS.

Measurements were made upon a non-salient-pole machine having the following particulars :—

Full-load continuous rating	25 amperes
Resistance of short-circuit path ..	0·37 ohm
Resistance of armature (wave-wound)	0·35 ohm
No. of poles	4
Ratio $\dfrac{\text{field ampere-turns}}{\text{armature ampere-turns}}$ ..	1·2

The rotor and stator conductors are wound in semi-closed slots, the stator winding being contained within 50 per cent of the periphery. The poles are non-salient and the stator iron is laminated. The predicted curves and the curves actually obtained by measurement are given in Fig. 9. It will be seen that above 300 r.p.m. the current is reasonably constant. The distortion of the field on the non-salient poles is probably responsible for the discrepancy between the actual and predicted short-circuit current. Although this distortion may affect commutation it is advan-

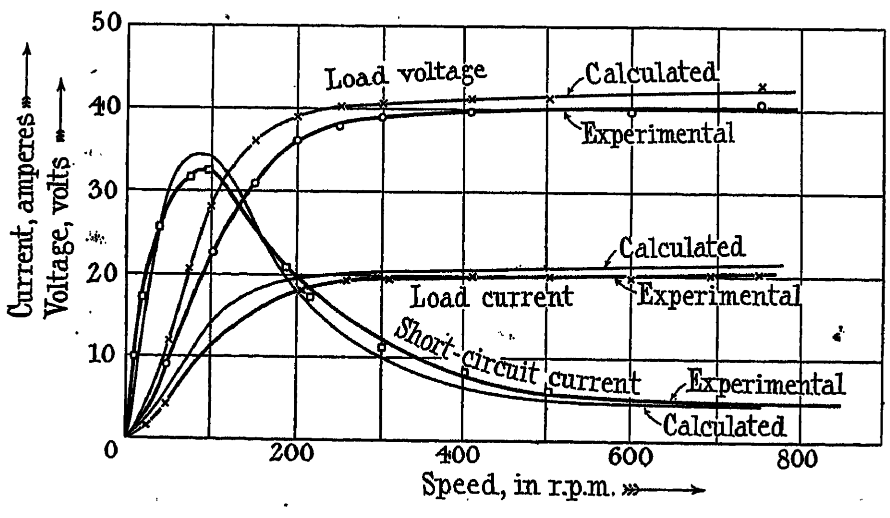

FIG. 9.

ing the points of intersection and is shown in the heavy-line curve of Fig. 6. The origin for this curve is O′.

The short-circuit characteristic.—The short-circuit current itself may also be obtained from Fig. 6. For

tageous in so far as it prevents the rise of the short-circuit current to the theoretical maximum, while the characteristic of the original Rosenberg machine with salient slotted poles is closely imitated.

APPENDIX.

Mathematical Expressions for Load Current and Short-Circuit Current.

If I is the short-circuit current and i the load current, we have

$$I = K'n\,(\phi - Ki/a) \quad . \quad . \quad . \quad . \quad (1)$$

where n = speed in revolutions per minute,
$K' = Zp/[R_s(10^8 \times 60)a]$,
Z = number of armature conductors,
p = number of poles,
a = number of parallel paths in the armature,
ϕ = flux per pole due to shunt field (constant),
R_s = resistance of short-circuit, and
$K = T'/0\cdot 8\rho$, ρ being the reluctance per pole of the main flux path and T' the cross-magnetizing turns per pole on the armature.

The main current i is directly proportional to the speed and to the flux produced by the short-circuit current in the armature.

$$i = K''\frac{In}{a} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where $K'' = ZT'p/[a(R_a + R_l)(10^8 \times 60)0\cdot 8\,\rho']$, ρ' being the reluctance per pole of the path of the short-circuit flux R_l the resistance of the load circuit, and R_a the armature resistance.

Combining Equations (1) and (2) we obtain

$$i = \frac{\phi}{a/(K''K'n^2) + K/a} \quad . \quad . \quad . \quad . \quad (3)$$

Substituting the values for K, K' and K'' this expression becomes

$$i = \phi \div \left[\left(\frac{10^8 \times 60 \times a}{Znp}\right)^2 \frac{(R_a+R_l)R_s a(0\cdot 8\rho')}{T'} + \frac{T'}{(0\cdot 8\rho)a}\right]$$

If a be the shunt field current and t' the number of turns per pole on the shunt field, we obtain

$$i = \frac{at'}{\dfrac{(0\cdot 23 \times 10^{20})(R_a + R_l)R_s\rho\rho' a^3}{(Zpn)^2 T} + \dfrac{T'}{a}} \quad . \quad (4)$$

Writing $T' = Z/(2p)$ this expression becomes

$$i = \frac{at'}{\dfrac{(0\cdot 46 \times 10^{20})(R_a + R_l)R_s\rho\rho' a^3}{Z^3 n^2 p} + \dfrac{Z}{2pa}} \quad . \quad (5)$$

In order that i may be practically independent of the speed (n) the first term in the denominator must be small compared with the second. Thus the number of turns on the armature must be large, as remarked by the late Dr. Kapp, and the speed must be high. The product of the reluctances ρ, ρ' of the main flux path and the short-circuit flux path appears in the numerator of the first term, and, therefore, both reluctances should be small. The reluctance of the short-circuit path may with advantage be kept low, but a low reluctance in the path of the main flux, although desirable at high speeds, will result in a heavy short-circuit current at low speeds when the load current is small. The short-circuit current at any given speed is proportional to the resultant main flux, which is equal to the difference between the flux due to the shunt field and that due to the load current in the armature. Thus at low speeds some means must be found to reduce the resultant flux. This is achieved by arranging that the field-magnet iron when under the influence of the shunt ampere-turns alone is highly saturated. In this way the maximum value of the shunt flux and, therefore, of the short-circuit current is kept within safe limits; while, when the machine is operating at speeds at which the load current is sensibly constant, the resultant flux is small and the reluctance of the main flux path therefore low. That is to say, under operating conditions when supplying load current the machine works on the lower part of the saturation curve.

On the assumption that the reluctances of the main flux path and the short-circuit flux path are constant over the whole range of speeds, an expression may be obtained for the maximum value of the short-circuit current.

Equations (1) and (2) combined to eliminate n give

$$I = K'\frac{ia}{IK''}\left(\Phi - K\frac{i}{a}\right) \quad . \quad . \quad . \quad . \quad (6)$$

Differentiating I with respect to i and equating to zero for the maximum value of the former gives

$$i = \frac{a\Phi}{2K}$$

The limiting value for i is such as to make $(\Phi - Ki/a) = 0$; this occurs when $i = a\Phi/K$. Thus the maximum short-circuit current flows when the load current has reached one-half of its final value. This approximation is justified fairly well by the curves in Fig. 9. Substituting this value $a\Phi/(2K)$ in Equation (6), the maximum value of the short-circuit current is

$$I = 0\cdot 8\frac{a\Phi p}{Z}\sqrt{\left[\frac{R_a + R_l}{R_s}\rho\rho'\right]} = i_{max.}\frac{0\cdot 5}{\rho}\sqrt{\left[\frac{R_a + R_l}{R_s}\rho\rho'\right]}$$

where $i_{max.}$ is the maximum load current which the machine is designed to supply.

In conclusion, the author wishes to express his thanks to Prof. E. W. Marchant, who has put at his disposal apparatus and instruments; to Dr. F. J. Teago, who has helped him with criticism and advice; and to Mr. J. W. Gibson, who has made the actual laboratory measurements.

THE PULLING INTO STEP OF A SYNCHRONOUS INDUCTION MOTOR.*

By H. COTTON, M.B.E., M.Sc., Associate Member.

(*Paper first received* 1*st March, and in final form* 22*nd October,* 1924.)

SUMMARY.

When studying the phenomenon of the pulling into step of a synchronous induction motor from the mathematical point of view, it is usually assumed that the synchronizing torque is a sinusoidal function of the angular distance between the stator and rotor fields. The following research points out that this is erroneous for several reasons, the most important of which is the effect of armature reaction. This sets up a double-frequency component in the synchronizing torque which very considerably modifies the conditions during synchronizing. The synchronizing torque of a salient-pole motor also possesses a double-frequency component but it is produced differently from that of the non-salient-pole motor. It is shown that the operation of the motor when this component is taken into account is amenable to mathematical solution.

An experimental investigation carried out on a small induction motor run as a synchronous motor is also described.

LIST OF SYMBOLS.

T_m = maximum value of synchronizing torque, in pounds-feet;
T_l = load torque, in pounds-feet;
T_i = induction-motor torque, in pounds-feet;
T_n = maximum value of double-frequency synchronizing torque in salient-pole machines;
T_s = total synchronizing torque = $F(\theta)$
$\xi = T_n/T_m$; $\rho = T_l/T_m$;
$\mathrm{I} = mr^2/g$ in pounds, feet and seconds, unless otherwise stated;
t = time, in seconds;
p = number of pole-pairs;
ω = slip, in mechanical radians per second;
$p\omega$ = slip, in electrical radians per second;
θ = angular distance between the stator and rotor fluxes, in electrical radians;
ω_0 = value of ω when $\theta = 0$;
S = synchronous speed, in mechanical radians per sec.;
N = actual speed, in revs. per minute;
E = applied P.D. per phase;
W = power developed per phase, in watts;
w = external load on the motor, in watts;
R = resistance per phase of the stator;
a = base of Blondel diagram;
b = radius of zero power circle in the diagram;
c = length of the back E.M.F. vector with constant excitation;
d = length of current vector;
r = radius of circle of any power;
α = base angle of Blondel diagram;
P = period of phase swing, in seconds.

THE NATURE OF THE SYNCHRONIZING TORQUE.

The most interesting characteristic of the synchronous induction motor is its behaviour during the transition period from induction-motor to synchronous-motor running.* This is essentially a dynamical problem, and in order to investigate the changes of motion that take place during this period it is necessary to establish the equation of slip motion of the rotor. Mathematical investigations of the slip motion have up to the present been made on the assumption that the synchronizing torque is proportional to sin θ, the corresponding equation being that given by Carr,† namely

$$-\rho T_m + T_m \sin\theta + \frac{\rho T_m}{p\omega}\cdot\frac{d\theta}{dt} + \frac{\mathrm{I}}{p}\cdot\frac{d^2\theta}{dt^2} = 0$$

This equation is erroneous for three reasons. First, the motor armature (the stator in most cases) possesses appreciable resistance as well as reactance. The effect of this is, as shown on page 212, to displace the curve of T_s along the θ axis without destroying its sinusoidal form. Secondly, if the speed at any instant is not exactly equal to the synchronous speed the exciting winding will be carrying induced alternating currents of low frequency in addition to the direct-current excitation. Thirdly, there is the effect of armature reaction on the motor back E.M.F. and therefore on the synchronizing torque. The effect of the superposition of direct and induced alternating rotor currents is explained as follows: The exciter gives a very low voltage, usually of the order of 30 or 40 volts in large machines, and its armature resistance is as a result very low. The presence of the armature in one phase of the rotor circuit will therefore make very litt'e difference to the distribution of induced alternating currents whenever the slip speed is not zero. The rotor flux will as a result be a varying and not a constant flux. The variations in exciter terminal voltage due to the slowly pulsating current flowing through its armature will produce additional variations in the exciting current, but these will in all probability be negligible. The effect is at present indeterminate because the equation of motion, even in the simple form it assumes when the rotor direct-current excitation is assumed to be constant, cannot be solved in the general case.

Consider next the effect of armature resistance. This can be deduced from the Blondel diagram shown in

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* The method of running induction motors at synchronous speed by introductory direct-current excitation into the secondary winding appears to have been first suggested by DANIELSON (*E.T.Z.*, 1901, vol. 22, p. 1065) and used for experimental researches by BRAGSTAD and LA COUR (*ibid.*, 1903, vol. 24, pp. 34 and 174).

† "The Pulling into Step of an Induction-Type Synchronous Motor," *Journal I.E.E.*, 1923, vol. 61, p. 692. The derivation of this equation has been given by the present author in the following: "Synchronous Motor Operation," *Electrician*, 1924, vol. 92, p. 220; and "The Synchronous Induction Motor," *World Power*, 1924, vol. 1, p. 329, and vol. 2, p. 45.

Fig. 1. In the triangle OAB, the base AB = applied P.D. (E) per phase, and the slant sides OA = OB = $E/(2R)$, where R is the armature resistance per phase. Circles drawn with centre O are lines of constant power utilized.

Let W = power per phase,
r = radius of power circle for power W.

Then
$$r = \frac{1}{2R}\sqrt{(E^2 - 4WR)}$$

With uniform angular velocity of the rotor and a constant torque the working point P will be fixed. We have from the diagram

PA = stator current,
PB = motor back E.M.F.,
∠ OAP = angle of lag of the current behind the applied P.D.

Now suppose that the excitation is constant and that the rotor is slipping through whole pole-pitches, then

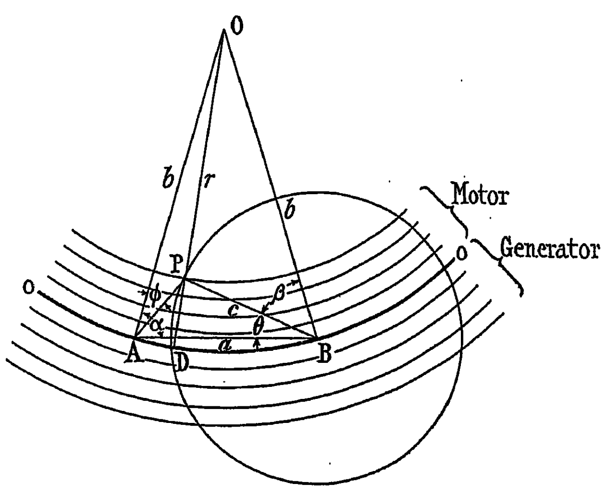

FIG. 1.

the vector BP will rotate about B as centre and will make one complete revolution for each pair of pole-pitches slipped by the rotor. The working point P will therefore pass over a whole family of circles of constant power. So long as P is above the circle of zero power, which passes through the points A and B, the machine will motor, but when it is below this circle the machine will function as a generator. The angle PBA is equal to the angle between the stator and rotor fields for any given position of the working point P; the angles OAB and OBA are fixed, being equal to α, say. Hence for the radius of the power circle for any given position of P we have

$$\begin{aligned} r &= \mathrm{OP} \\ &= \sqrt{(\mathrm{OB}^2 + \mathrm{PB}^2 - 2\mathrm{OB}\cdot\mathrm{PB}\cos\mathrm{OBP})} \\ &= \sqrt{(b^2 + c^2 - 2bc\cos\beta)} \end{aligned}$$

If we put

$$m = \frac{\text{power utilized}}{\text{maximum possible power}}$$

then
$$r^2 = b^2(1 - m)$$

from which it follows that

$$\cos\beta = \frac{c^2 + mb^2}{2bc}$$

or
$$m = \frac{2bc\cos\beta - c^2}{b^2}$$

Hence the power utilized is a sinusoidal function of the angle β, and therefore of the angle θ. This so far agrees with the reasoning of Lindstrom,* who considers a simpler form of diagram than the Blondel diagram. But whereas Lindstrom obtains zero power when θ is equal to 0° or 180°, we see that the angle θ is finite for zero power, its magnitude being then given by

$$\cos(\alpha - \theta) = \cos\beta = \frac{c^2}{2bc} \text{ when } m = 0$$

$$\begin{aligned} \therefore\quad \theta &= \alpha - \operatorname{arc\,cos}\frac{c}{2b} \\ &= \operatorname{arc\,cos}\frac{a}{2b} - \operatorname{arc\,cos}\frac{c}{2b} \\ &= 0 \text{ when } c = a \end{aligned}$$

Hence the motor only gives zero power when θ is zero in the special case in which the excitation is such that the vector c representing the motor back E.M.F. is numerically equal to the vector a representing the applied P.D. In an actual case the base angles of the triangle OAB are so very nearly equal to right angles that the displacement of the curve of T_s along the axis is very small. Experimental results are given on page 217.

The effect of the varying excitation due to the superposition of the direct and alternating currents in the rotor is to modify the motor back E.M.F., the result being that the back E.M.F. is not constant but varies with θ. This obviously causes the curve of T_s to depart from the sinusoidal form, since the path of the working point P as the motor slips two pole-pitches will no longer be truly circular.

Consider now the effect of armature reaction. Let the various lengths and angles be represented by the symbols denoted in Fig. 2. Since the magnitude of the armature reaction is proportional to the current I and therefore to the resultant E.M.F., or the vector AP of length d in the figure, and its magnetizing or demagnetizing effect is proportional to the sine of the internal angle of lag (or lead) ϕ (or $180 - \phi$), we have for the back E.M.F. at any instant

$$\begin{aligned} E_b &= c \pm pI\sin\phi \\ &= c \pm qE_r\sin\phi \\ &= c \pm qd\sin\phi\ \dagger \end{aligned}$$

where p and q are constants which can be determined experimentally for a given machine, E_r the resultant E.M.F. per phase, and c the length of the back E.M.F.

* A. LINDSTROM: "Auto-Synchronous Motors," *Electrician*, 1923, vol. 91, pp. 4 and 64.

† The current always leads the internal E.M.F., whether the machine is motoring or generating, because in the only case that need be considered the internal E.M.F. is greater than the applied E.M.F. Hence the minus sign is used when the machine is motoring, and the plus sign when it is generating.

vector for the given excitation on no load. Hence we have

$$a^2 + d^2 - 2ad\cos(90 - \psi) = (c \pm qd \sin\phi)^2$$

$$\therefore\ a^2 + d^2 - 2ad\sin\psi \qquad = (c \pm qd\sin\phi)^2$$

Put

$$d\sin\psi = x$$

$$d\cos\psi = y$$

and simplify the diagram by making the angles OAB and OBA right angles, which they very nearly are in an actual machine. Then

$$a^2 + x^2 + y^2 - 2ax = (c \pm qd\sin\phi)^2$$

Now

$$\phi = 180 + \psi - \theta$$

$$\therefore\ a^2 + x^2 + y^2 - 2ax$$

$$= \{c \pm qd\sin(180 + \psi - \theta)\}^2$$

$$= \{c \mp qd(\sin\psi\cos\theta - \cos\psi\sin\theta)\}^2$$

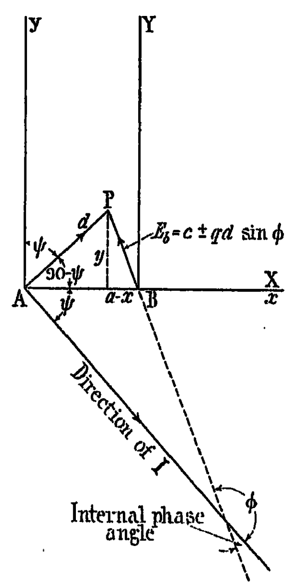

FIG. 2.

Again, to eliminate θ we have

$$\tan\theta = \frac{y}{a - x}$$

$$\sin\theta = \frac{y}{\sqrt{(a^2 - 2ax + x^2 + y^2)}}$$

and

$$\cos\theta = \frac{a - x}{\sqrt{(a^2 - 2ax + x^2 + y^2)}}$$

Substituting these values we have

$$a^2+x^2+y^2-2ax = \left\{c \mp qd\left(\sin\psi \times \frac{a-x}{\sqrt{\{(x-a)^2+y^2\}}} - \cos\psi \times \frac{y}{\sqrt{\{(x-a)^2+y^2\}}}\right)\right\}^2$$

This reduces to

$$\{a^2 + (1 \mp q)x^2 - 2ax(1 \mp q)\} \mp qax + (1 \mp q)y^2 = c\sqrt{\{(x-a)^2 + y^2\}}$$

Now put

$$x - a = X$$

$$y = Y$$

thus transferring the origin from A to B.

$$\therefore\ (1 \mp q)\{a^2 + x^2 - 2ax\} \pm qa^2 \mp qax + (1 \mp q)y^2 = c\sqrt{\{(x-a)^2 + y^2\}}$$

$$\therefore\ (1 \mp q)X^2 \pm qa^2 \mp qa(X + a) + (1 \pm q)Y^2 = c\sqrt{(X^2 + Y^2)}$$

$$\therefore\ X^2 + Y^2 \mp \frac{qa}{1 \mp q}X = \frac{c}{1 \mp q}\sqrt{(X^2 + Y^2)}$$

This is a quartic,* but it can be simplified by converting from rectangular to polar co-ordinates. Remembering that the angle θ is the supplement of the angle included between the rotating vector BP and the positive direction of X, we have

$$X^2 + Y^2 = r^2$$

$$X = -r\cos\theta$$

$$\therefore\ r^2 \pm \frac{qa}{1 \mp q} r\cos\theta = \frac{c}{1 \mp q} r$$

$$r = \frac{c \mp qa\cos\theta}{1 \mp q}$$

Also for the synchronizing power corresponding to any angle we have the perpendicular distance

$$Y = r\sin\theta$$

$$= \frac{c\sin\theta \mp \frac{1}{2}qa\sin 2\theta}{1 \mp q}$$

We see from this that the synchronizing power, and therefore the synchronizing torque, possesses a double-frequency component.

Thus the synchronizing torque is no longer a simple sinusoidal function of θ, the extent of its departure from this form depending upon the magnitude of the constant q. When q is zero we have $r = c$, the locus of P then being the circumference of a circle with centre B and radius equal to the constant motor back E.M.F. An actual experimental case is considered below. If we take the effect of armature reaction into account and put

$$T_s = F(\theta)$$

where F is a function which can be determined either by experiment or from the design data of the motor, then

$$-\rho T_m + F(\theta) + \frac{\rho T_m}{p\omega}\cdot\frac{d\theta}{dt} + \frac{\mathrm{I}}{p}\cdot\frac{d^2\theta}{dt^2} = 0$$

The direct solution of either the approximate or the more exact form of the equation appears to be impossible, so that it is necessary to consider a special case and make use of a step-by-step solution.

EXPERIMENTAL INVESTIGATION.

The whole of the experimental work given in this section of the paper refers to the case of a plain induction

* A somewhat similar problem relating to a salient-pole machine is discussed by E. B. SHAND (*Electric Journal*, 1921 vol. 18, p. 309), who obtains an elliptic locus.

motor synchronized by switching direct current on to the rotor. The specification of this motor is as follows :—

Number of poles	4
Horse-power	2
Voltage	245
Frequency	50

It would have been preferable to have performed the experiments on a larger machine, but unfortunately one was not available. The small size of the machine introduced many difficulties which in all probability would not have existed with a larger machine.

Moment of inertia of the rotor.—The rotor was drawn, and its moment of inertia determined from its time of oscillation in a bifilar suspension was

$I = 4\cdot32$ in ft.-lb. units, or $0\cdot182$ in metre-kg units.

Retarding torque.—In the experiment conducted to

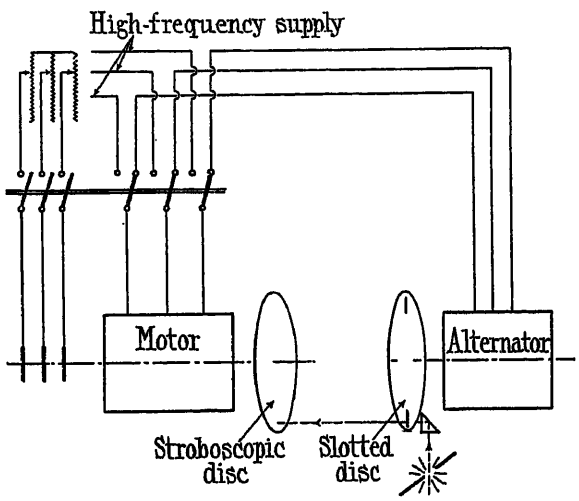

FIG. 3.

determine the changes of slip motion during the process of synchronizing, the motor was run on a small frictional load. The retarding torque at any instant was therefore that due to the iron and total friction losses at that instant. Since the speed of the motor is raised from $S(1 - \sigma)$ to S during the process of synchronizing, the torque corresponding to the mean speed $S(1 - \frac{1}{2}\sigma)$ was used in calculating the value of ρ in the equation of motion. The loss was determined by the retardation method, using a stroboscopic disc of the pattern devised by Robertson. Since the slowing down was very rapid the time was determined by means of a chronograph time marked at 1-second intervals by a seconds pendulum as suggested in an article published * by the author. The losses occurring at a speed greater than the normal induction motor speed were required, and it was therefore necessary to arrange for the motor to run down through synchronous speed. This was done by placing a three-pole double-throw switch in the stator circuit so that the stator could be switched on to either of two independent supplies, one of them of normal frequency and the other with a frequency greater than normal. The motor was run up to full speed on the high-frequency supply and the switch was suddenly thrown over on to the normal-frequency supply. At the same instant the rotor circuit was opened. The stroboscopic disc was illuminated by means of an arc lamp, the light being rendered intermittent by causing it to pass through slits in the periphery of a cardboard disc mounted on the shaft of the alternator giving the normal-frequency supply.* The arrangement of the test is shown in Fig. 3.

The synchronous speed of the rotor was 1 500 r.p.m. The slip speed when running on the small frictional load as a plain induction motor was 38 r.p.m. The percentage slip was therefore $2\cdot53$, and the mean of

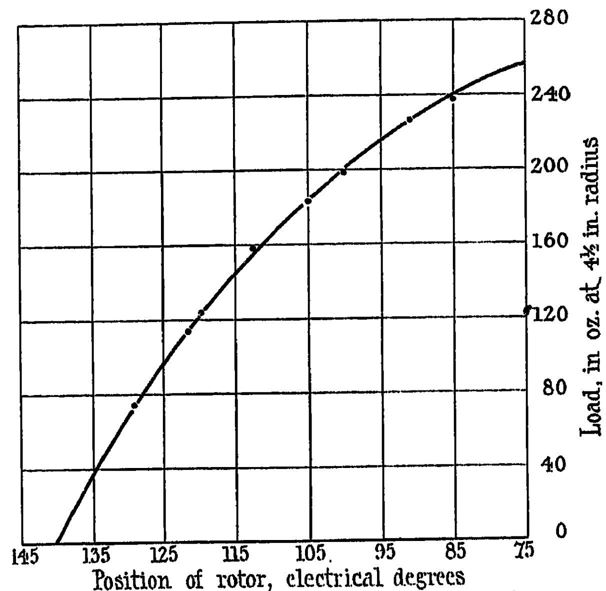

FIG. 4.

the induction motor speed and synchronous speed was 1 481 r.p.m. The rate of deceleration at this speed

$$\frac{dN}{dt} = 122 \text{ r.p.m. per sec.}$$
$$N = 1\,481 \text{ r.p.m.}$$

Hence the load on the motor at the mean speed

$$w = 0\cdot0109\, IN\frac{dN}{dt}$$
$$= 362 \text{ watts}$$

The corresponding retarding torque in lb.-ft. units is

$$T_l = \frac{33\,000}{2\pi \times 1\,481 \times 746} \times w$$
$$= 1\cdot725 \text{ lb.-ft. units.}$$

Pull-out torque when operating as a synchronous motor.—The pull-out torque T_m was determined as follows. The stroboscopic disc on the motor shaft was illuminated

* "The Retardation Method of Determining the Losses in Electrical Machines," *Beama*, 1922, vol. 11, p. 128.

* This method of illumination gives a beautifully clear and steady pattern and is much superior to the Bruckmann method (*Electrician*, 1911, vol. 67, p. 890).

intermittently by means of the slotted disc on the alternator shaft, as shown in Fig. 3. Direct current was switched on to the rotor circuit and the motor pulled into step, the pattern on the disc becoming stationary. The direct-current rotor excitation was kept at 10 amperes for the experimental work. A scale graduated in electrical degrees was placed just behind the stroboscopic disc and it was thus possible to read off the position of any one point on the pattern. The motor was then loaded by means of a band brake and the angular position of the pattern was read off for different values of the retarding torque. The load was gradually increased until the pattern began to be unsteady, indicating that the pull-out torque was very nearly reached. The load was then very gradually increased by hand, but no additional spring-balance readings were taken, and the maximum displacement of the pattern prior to the motor falling out of step was noted. The success of a test of this kind depends entirely upon the clearness and steadiness of the pattern on the disc. With the method of illumination previously described the pattern was almost as distinct as when stationary, flickering taking place only when the position of instability was nearly reached.

TABLE 1.

(Load torque $T_l = 1 \cdot 725$ lb.-ft.
$= 74$ oz. acting at $4\frac{1}{2}$ in. radius)
Diameter of pulley for load test = 9 in.

External load. Difference of spring-balance readings	Total load	Position of pattern
	oz.	
—	74	129
40	114	121·5
50	124	119·5
84	158	112·5
109	183	105
125	199	100
152	226	91
164	238	85
Pulled out at	—	75

The results of this test are given in Table 1 and plotted in Fig. 4. The friction-loss torque as determined by the running-down test was added to the torque due to the brake, and by producing the curve to cut the horizontal axis the position of the pattern for zero retarding torque was found. At this position the poles of the stator and rotor fields were exactly in line and therefore the angle θ in the equation of motion was zero. This point was therefore the zero for the angle θ and was used as such in the synchronizing tests.

From the curve we see that

$$T_m = 6 \cdot 04 \text{ lb.-ft. } (258 \text{ oz. at } 4\tfrac{1}{2} \text{ in. radius})$$

But $$T_l = 1 \cdot 725 \text{ lb.-ft. } (74 \text{ oz. at } 4\tfrac{1}{2} \text{ in. radius})$$

hence $$\rho = T_l/T_m = 0 \cdot 286$$

The variation of the synchronizing torque with the angle θ.—It has been shown previously that the expression $T_s = T_m \sin \theta$ is only approximate, and it is desirable to know what degree of error is involved in the assumption.

It was necessary to adopt an analytical method, making use of the Blondel diagram. In order that the construction of this diagram may be possible, the stator resistance and synchronous impedance when the motor is functioning as a synchronous motor must be determined. The stator resistance R was $1 \cdot 25$ ohms per phase. The synchronous impedance was found both by the

TABLE 2.

(1) *Open-Circuit Test at* 1 500 *r.p.m.*

Excitation	Terminal E.M.F.
amps.	volts
15	222·2
14	218·6
13	214·0
12	209·4
11	203·3
10	196·0
9	187·8
8	181·5
7	169·5
6	157·2
5	138·5
4	122·2
3	96·3
2	66·2
1	35·9

(2) *Short-Circuit Test.*

Excitation	Amm. 1	Amm. 2	Mean
amps.	amps.	amps.	amps.
15·7	4·75	4·8	4·78
14·1	4·23	4·28	4·26
12·0	3·58	3·65	3·62
10·0	3·0	3·0	3·0
8·15	2·34	2·35	2·35
5·8	1·73	1·77	1·75
4·1	1·17	1·18	1·18
2·9	0·85	0·90	0·88

(3) *Wattless-Current Test at Constant Current of* 3 *amperes.*

Excitation	Terminal P.D.
amps.	volts
10	—
11·7	29
13	39·5
14	50
15·5	62

short-circuit (Behn-Eschenberg) method, and by the wattless current method. The motor was belt-driven and run as a synchronous alternator at 1 500 r.p.m., and the rotor was excited from a battery, the range of excitation being from 0 to 15 amperes. Because of the magnetic weakness of the field system (rotor) as compared with the stator—due to the small air-gap and the comparatively small number of rotor turns—it was necessary to make an allowance for the armature reaction. This was determined by putting the machine on a choker load while running as an alternator. The current was kept constant during this test, and was adjusted to be equal to the short-circuit current corresponding to an excitation of 10 amperes (the excitation used in the synchronous motor tests). The experimental results

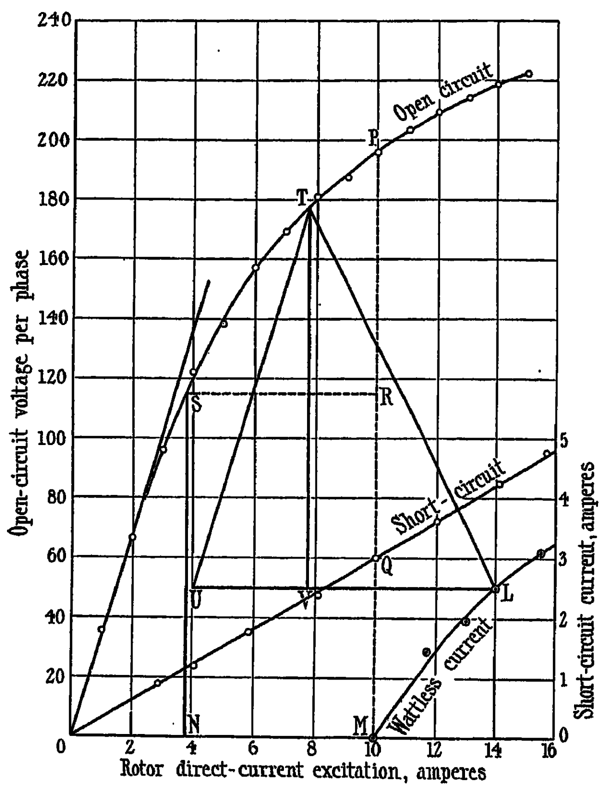

FIG. 5.

for these tests are given in Table 2 and are plotted in Fig. 5. The open-circuit and short-circuit results give very smooth curves, but that for the wattless-current characteristic is rather irregular. This is probably due to the fact that the belt fastener caused the instrument needles to oscillate much more violently during the wattless-current test than in the other tests. It will be noticed that these characteristics are very different from those of a salient-pole alternator because the relative magnetic importance of the armature and field is reversed. This is shown by the fact that the short-circuit current with a rotor excitation equal to the rotor full-load current was less than the normal full-load current.

The terminal voltage on wattless current with 10 amperes excitation was 50, the corresponding point being L in Fig. 5. By the ordinary Potier construction the triangle TUL was obtained, thus giving

Demagnetizing armature reaction, equivalent to LV, i.e. to 6·25 amperes excitation.
Reactance voltage per phase, TV = 128 volts.
Armature current = 3 amperes.
∴ Impedance per phase, $Z = 128/3 = 42\cdot7$ ohms.

In applying the Behn-Eschenberg method we have for the resultant excitation, after deducting that due to armature reaction,

$$\begin{aligned} ON &= 10 - 6\cdot25 \\ &= 3\cdot75 \text{ amperes.} \end{aligned}$$

Corresponding induced voltage per phase

$$SN = 115 \text{ volts.}$$

Short-circuit current with 10 amperes excitation

$$= 3 \text{ amperes.}$$

∴ Synchronous impedance per phase

$$= 115/3 = 38\cdot3 \text{ ohms.}$$

Thus the wattless-current method gave a greater impedance than the Behn-Eschenberg method, the reverse of what is usually found. The reason for this is that owing to the high armature impedance and the very great demagnetizing effect of the armature reaction it was not necessary to apply a reduced excitation when determining the short-circuit characteristic. In fact, as explained above, a current equal to the normal current could only be obtained by applying a considerably increased excitation. It is therefore reasonable to expect the wattless-current method to give the greater synchronous impedance in this case.

In calculating the Blondel diagram the mean value of the synchronous impedance was taken, namely, $Z = 40\cdot5$ ohms.

The normal applied stator voltage was 245 V at the terminals and therefore 143 V per phase. The base line AB of the Blondel diagram (Fig. 1) is therefore made proportional to 143. The base angles of the triangle BOA are each 88° 14′.

The hypotenuse has a length

$$\begin{aligned} OB &= 143 \times \frac{Z}{2R} \\ &= 2\,310 \end{aligned}$$

Now the maximum possible power per phase is given by

$$\begin{aligned} \frac{E^2}{4R} &= \frac{143^2}{5} \\ &= 4\,100 \text{ watts} \end{aligned}$$

Hence the maximum possible power for three phases

$$= 12\,300 \text{ watts}$$

The corresponding power circle is the circle of centre O and of zero radius, namely the point O.

Now, from the figure, the motor back E.M.F. per phase with 10 amperes excitation and zero armature

reaction is 196 volts. Hence the radius of the circle of maximum power developed with this excitation, namely the maximum power of the motor, is

$$\begin{aligned} r &= 2\,310 - 196 \\ &= 2\,114 \end{aligned}$$

Hence if m is the ratio between this power and the maximum possible power of 12 300 watts we have

$$2\,114 = 2\,310\sqrt{(1 - m)}$$

therefore $m = 0\cdot163$

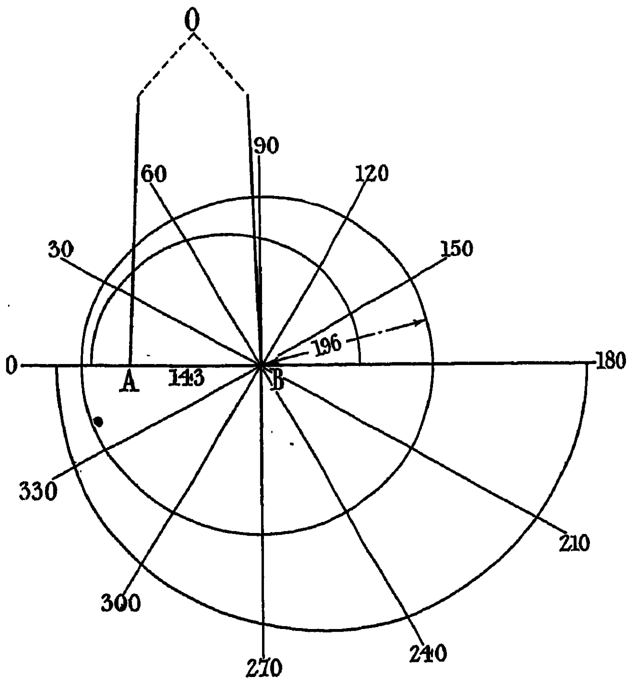

FIG. 6.

Hence maximum power developed with 10 amperes excitation

$$\begin{aligned} &= 0\cdot163 \times 12\,300 \\ &= 2\,000 \text{ watts} \\ &= 2\cdot68 \text{ h.p.} \end{aligned}$$

The pull-out torque of the motor is therefore

$$\begin{aligned} T_m &= \frac{2\cdot68 \times 33\,000}{2 \times 1\,500} \\ &= 9\cdot4 \text{ lb.-ft. or } 113 \text{ lb.-in.} \end{aligned}$$

This is considerably greater than the experimentally determined value of 72·5 lb.-in., but it is obvious that with such a small machine and with such unusual conditions for the determination of the synchronous impedance and armature reaction, close agreement is impossible. In addition the correction for armature reaction has yet to be applied. In determining the changes taking place during the process of synchronizing, the experimentally observed value of T_m was therefore used, but in the investigation of the deviation of T_m from the assumed sinusoidal form the value given by the Blondel diagram was used because the theory of the method is based on the diagram.

The radii of the circles of constant power W are given by the expression

$$\begin{aligned} r &= 2\,310\sqrt{(1 - W/12\,300)} \\ &= 2\,310(1 - W/24\,600) \text{ approx.,} \end{aligned}$$

when m is small. Thus when the excitation is such that the maximum power developed by the motor is a small fraction of the maximum possible power, the circles of constant power for the range of working of the motor are spaced equidistantly.

When the power developed is 2 000 watts we have seen that the radius of the power circle is 2 114. The radius of the circle of maximum power in the generating region of the diagram is

$$2\,310 + 196 = 2\,506$$

for which the corresponding power is

$$W = 2\,200 \text{ watts.}$$

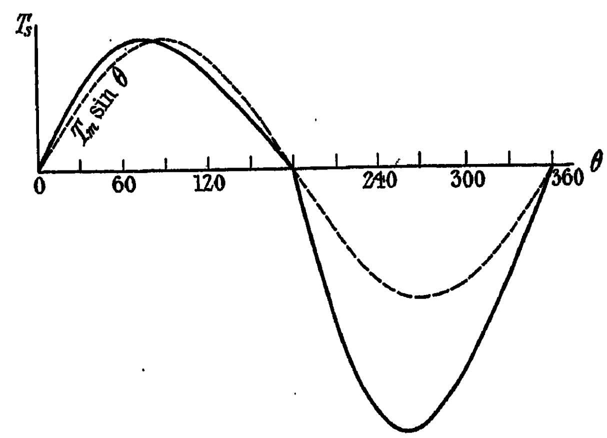

FIG. 7.

If the motor slips two pole-pitches the back E.M.F. vector will make one complete revolution and its extremity will fall in turn on to each of the circles of constant power within the working range. The back E.M.F. vector is drawn in the enlarged diagram in Fig. 6 at intervals of 30°, and the power is plotted as a function of θ in Fig. 7. This curve gives the variation of power and therefore of synchronizing torque on the assumption that the armature reaction can be neglected. It has been shown on page 212 that it is a sinusoidal function of θ, and also, since the base angle of the triangle AOB is nearly 90°, its displacement from the curve of $T_m \sin\theta$ is very small. We have seen that the armature reaction cannot be neglected and it is therefore necessary to make a correction for it. This correction is applied as follows. The vector AP measured on the voltage scale gives the resultant E.M.F. in the armature circuit. Hence it is proportional to the armature current. Now the demagnetizing effect of the armature reaction for a current of 3 amperes lagging approximately 90° was found from the wattless-current test to be equivalent to 6·25 amperes of excitation. Hence for any

armature current I with an internal angle of lag ϕ we have:—

Excitation equivalent to the armature reaction

$$= \tfrac{1}{3}I \times 6\cdot25 \sin\phi$$
$$= 2\cdot08 I \sin\phi$$

In Fig. 8 a portion of the open-circuit characteristic in the neighbourhood of an excitation of 10 amperes is drawn. The mean value of the excitation during one whole revolution of phase-swing was 10 amperes in the experiments, and from the construction we see that a variation of excitation of 2·08 amperes about the mean value (10 amperes) was equivalent to an induced voltage of 14·6. The mean value of the induced voltage was 196 volts.

Expressing by E_r the resultant E.M.F. per phase we have for the current per phase

$$I = \frac{E_r}{42\cdot7} = \frac{d}{42\cdot7} \text{ (see Fig. 2)}$$

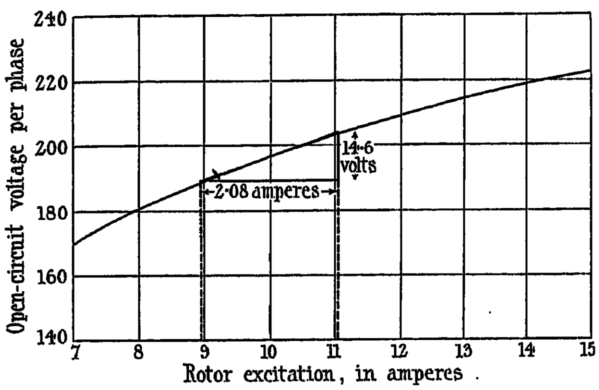

FIG. 8.

The armature reaction was therefore equivalent to a voltage of

$$\frac{d}{42\cdot7} \times 14\cdot6 \sin\phi = 0\cdot34 d \sin\phi$$

from which we see that for the value of the constant q in the equation for the back E.M.F. per phase

$$E_b = c \pm q \sin\phi$$

we have $q = 0\cdot34$.

Hence for the polar equation to the locus of the extremity of the back E.M.F. vector we have

$$r = \frac{c \pm qa \cos\theta}{1 \pm q}$$

Now $c = 196$; $a = 143$; and $q = 0\cdot34$.

$$\therefore\ r = \frac{196 \pm 48\cdot5 \cos\theta}{1 \pm 0\cdot34}$$
$$= 146 + 36\cdot2 \cos\theta$$
or
$$297 - 73\cdot5 \cos\theta$$

This is plotted in Fig. 6, the circle of radius $C = 196$ being drawn for comparison.

The Y co-ordinate of any point on the locus is given by

$$\mathrm{OY} = \frac{c \sin\theta \pm \tfrac{1}{2} qa \sin 2\theta}{1 \pm q}$$
$$= 146 \sin\theta + 18\cdot1 \sin 2\theta$$
or
$$297 \sin\theta - 36\cdot8 \sin 2\theta$$

Now a perpendicular distance of 196 volts corresponds to a torque of 9·42 lb.-ft. using the Blondel diagram. Hence the corrected expression for the synchronizing torque in terms of the angle θ is, when functioning as a motor,

$$T_s = \frac{9\cdot42}{196}(146 \sin\theta + 18\cdot1 \sin 2\theta)$$
$$= 7 \sin\theta + 0\cdot87 \sin 2\theta$$

This is compared with the sinusoidal form

$$T_s = 9\cdot42 \sin\theta$$

in Fig. 7, and it is obvious that there is a very considerable difference between the actual values of the synchronizing torque and those usually assumed. From the equation for T_s we have

$$\frac{dT_s}{d\theta} = 7 \cos\theta + 1\cdot74 \cos 2\theta$$

$= 0$ and corresponds to a maximum when

$\cos\theta = 0\cdot23$

or $\theta = 76\cdot5°$ (approx.)

If the synchronizing torque were a sinusoidal function of the angle the motor should fall out of step when the load has increased to such an extent that θ is equal to 90°. It is well known that a displacement of 90° is never attained. In the case of the 2-h.p. motor under test the displacement was 65° (see Fig. 4). The maximum value of the synchronizing torque from the Blondel diagram corrected for armature reaction is

$$T_m = 7 \sin 76\cdot5° + 0\cdot87 \sin 153°$$
$$= 7\cdot2 \text{ lb.-ft.}$$

This is in reasonable agreement with the experimentally observed value of 6·04.

Phase-swinging subsequent to the excitation of the rotor.—In previous experimental investigations of the variations in current and in speed which take place immediately after the direct-current excitation has been switched on to the rotor, some idea of the rotor position has been obtained from the position of the pointer of the ammeter in the rotor circuit. A complete record of changes corresponding to switching in at θ equal to 0, 20, 40, 60, etc., up to 360 electrical degrees was required for the present investigation. The stroboscopic method was therefore used, the excitation being switched on at the moment the pattern on the disc coincided with a division on the scale. Because of the fairly rapid movement of the pattern it was practically impossible to manipulate an ordinary throw-over switch sufficiently quickly. A special quick-change switch was therefore made by placing a second row of contacts at an angular distance of about 30° from the contacts of an ordinary slow-break three-pole switch. When breaking with one set of contacts the blades were about $\tfrac{1}{8}$ in. from the

second set, the result being that a very quick change-over could be made and the excitation switched on without much appreciable time-lag.

The variations in rotor current are given in the oscillograms of Fig. 9 and show very clearly how the correct moment for excitation depends upon the angle θ.

The variations in speed were next determined. In the case of a large machine having its own exciter the obvious method is to excite the exciter separately and use it as a speed indicator, neutralizing the voltage induced in its armature when running uniformly at full induction-motor speed. The oscillograph then gives the variations of speed only. This method is certainly the most convenient but it suffers from the disadvantage that since the exciters are very low-voltage machines they have a very pronounced commutator ripple which somewhat impairs the clearness of the curve of speed variation. The machine under test had no d.c. machine coupled to it, and therefore after much experiment the following method was adopted :—

A german-silver disc keyed to the induction-motor shaft rotated between the poles of an electro-magnet, and two flexible brass clips were used as collectors. On running at 1 500 r.p.m. an E.M.F. of about 200 millivolts was obtained, the E.M.F. corresponding to slip speed being therefore in the neighbourhood of 6 millivolts. When running steadily the E.M.F. was balanced out by a potentiometer slide, thus leaving the small E.M.F. due to the variations in slip to operate the oscillograph. This E.M.F. was magnified by a thermionic valve (Marconi-Osram type LS 2) which was worked with a plate potential of 400 volts and a filament current of 1·3 amperes. Since the frequency of the variations was so very low, transformers were not used. The amplifying circuit is shown in Fig. 10. When it was found that the valve acted in a

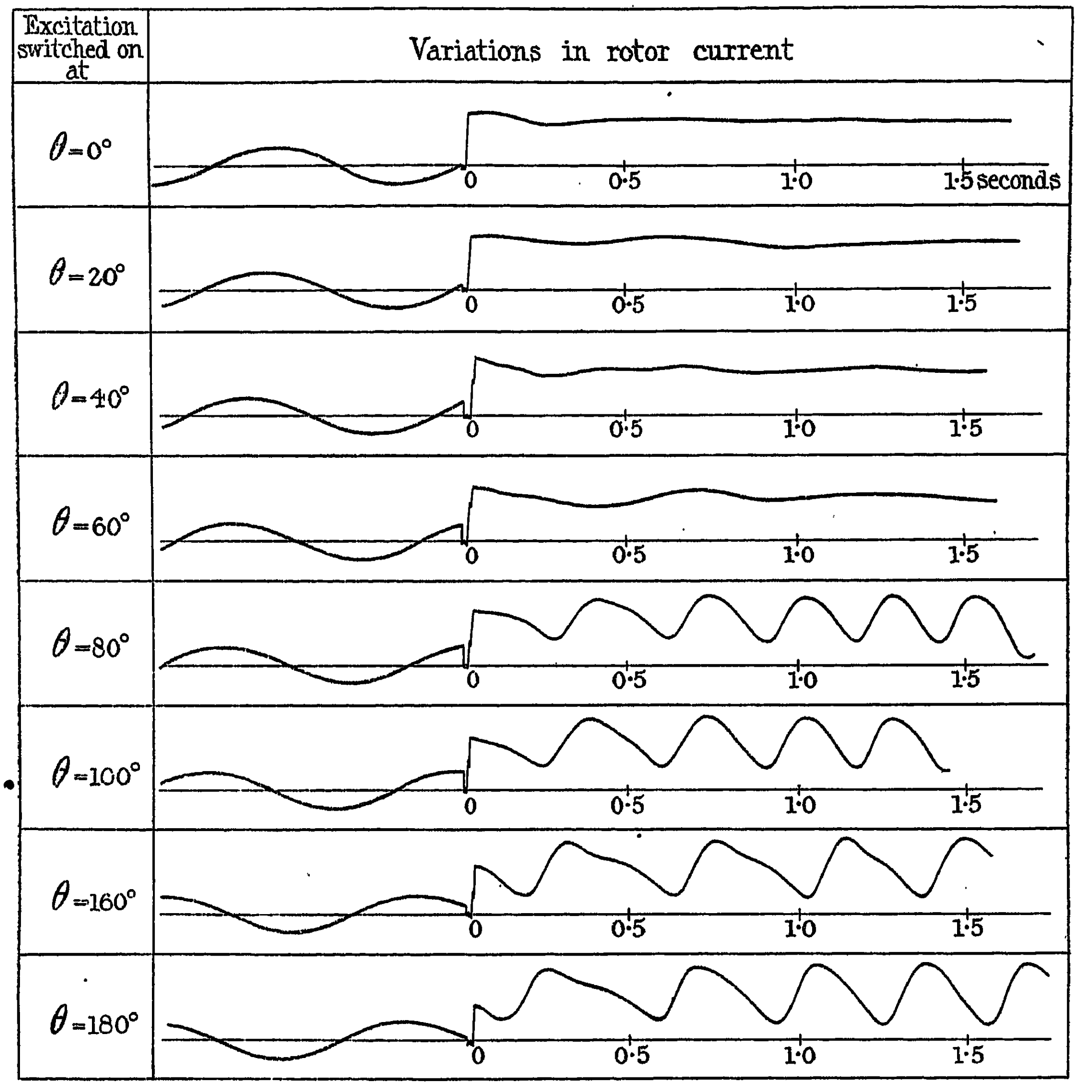

FIG. 9.

satisfactory manner as an amplifier the characteristic was determined in order to ensure that it was worked on the straight portion, thus producing no appreciable distortion.

The slip curves in Fig. 11 show two sets of ripples due to the following causes. First, there is a comparatively low-frequency ripple due to a slight wobble in the rotating disc; and secondly a high-frequency ripple the two horizontal portions on the curves is equal to the slip speed of 38 r.p.m., the curves are automatically calibrated for speed. Time marking was effected by sending through the second vibrator a very small alternating current whose frequency was 45 cycles per second.

The above method has the advantage that it liberates the exciter (in the case of a commercial machine) to

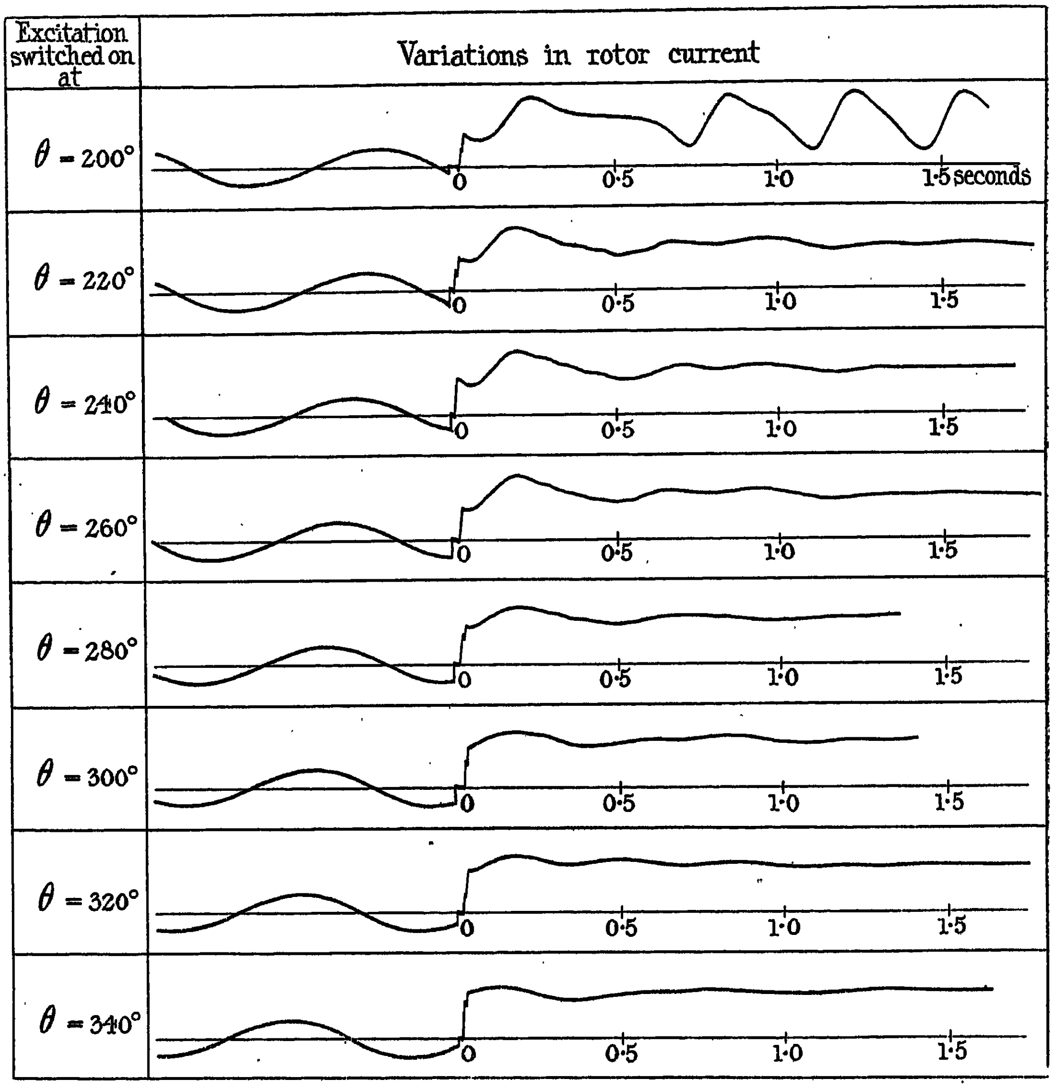

FIG. 9 (*continued*).

due to variations in plate voltage. This was a commutator ripple on the voltage of a d.c. generator used for this purpose as a battery of sufficiently high voltage was not available. It will be seen that it is possible to eliminate these ripples, and the author believes that this is the only method by which the speed variations can be determined experimentally in the form of smooth curves. The amplitude was not very large and therefore the mirror giving the zero line was put out of action in order to avoid confusion. Since the distance between carry out its proper function. This is desirable since, as pointed out on page 224, the variations of exciter voltage must have some influence on the conditions of pulling into step, especially for those values of θ for which the chances of synchronizing or not are almost equal.

The period of whole revolutions of slip.—The equation of motion for no-load conditions is

$$\ddot{\theta} + \frac{T_m p}{I} \sin \theta = 0$$

assuming $T_s = T_m \sin\theta$, and the period for small oscillations is

$$P = 2\pi\sqrt{\left(\frac{\mathrm{I}}{T_m p}\right)}$$

Comparing this with the period for a simple pendulum

$$P = 2\pi\sqrt{\left(\frac{l}{g}\right)}$$

we have for the length of the equivalent simple pendulum

$$l = \frac{\mathrm{I}g}{T_m p}$$

In the case of the simple pendulum, if the angular velocity when the position $\theta = 0$ is greater than $2\sqrt{(l/g)}$ the pendulum will make complete revolutions. Supposing that the angular velocity in this position is numerically equal to the velocity attained by falling

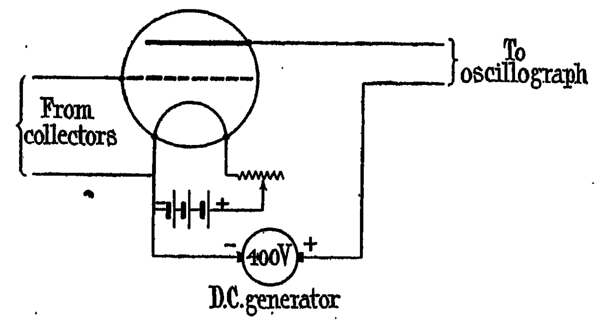

FIG. 10.

freely from a height $2h(>2l)$, then the period of a revolution will be

$$P = \pi\sqrt{\left(\frac{4l^2}{gh}\right)}\left\{1 + (\tfrac{1}{2})^2\frac{l}{h} + \left(\frac{1\,.\,3}{2\,.\,4}\right)^2\frac{l^2}{h^2} + \left(\frac{1\,.\,3\,.\,5}{2\,.\,4\,.\,6}\right)^2\frac{l^3}{h^3} + \ldots\right\}^*$$

In the case of the motor we have for the height $2h$ from which a linear velocity numerically equal to ω_0 will be attained (the radius of the disc in the mechanical model † being unity),

$$\omega_0^2 = 4gh$$

$$h = \frac{\omega_0^2}{4g}\ ‡$$

Hence for the period of one revolution we have

$$P = \pi + \frac{2\mathrm{I}g}{T_m p\omega_0}\left\{1 + (\tfrac{1}{2})^2 \cdot \frac{4\mathrm{I}g^2}{T_m p\omega_0^2} + \left(\frac{1\,.\,3}{2\,.\,4}\right)\left(\frac{4\mathrm{I}g^2}{T_m p\omega_0^2}\right)^2 + \ldots\right\}$$

From the speed curves of Fig. 11 we see that the maximum value of ω_0 is about $6{\cdot}75$ mechanical radians per sec.

$= 13{\cdot}5$ electrical radians per sec.

$T_m = 6{\cdot}04$ lb.-ft.; $p = 2$ and $g = 32$

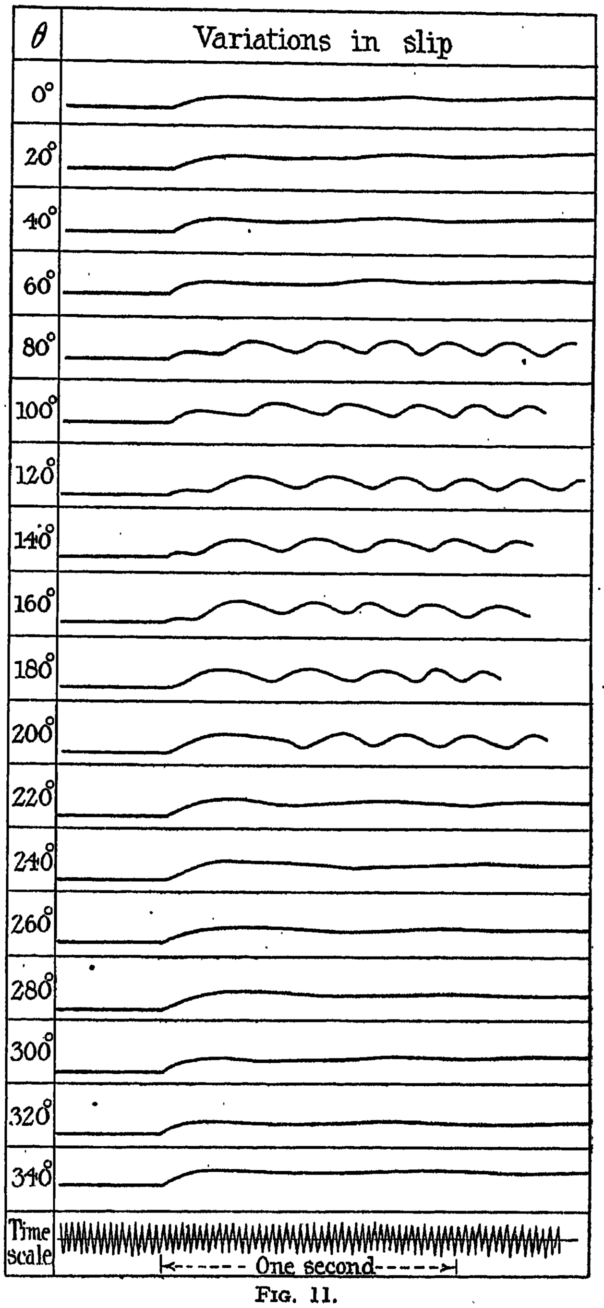

FIG. 11.

Hence $$\frac{2\mathrm{I}g}{T_m p\omega_0} = 0{\cdot}054$$

where I is in ft.-lb.-sec. units, and T_m is in lb.-ft.,

and $$\frac{4\mathrm{I}g^2}{T_m p\omega_0^2} = 0{\cdot}26$$

$$\therefore\ P = \pi \times 0{\cdot}054\{1 + \tfrac{1}{4} \times 0{\cdot}26 + \tfrac{9}{64} \times (0{\cdot}26)^2 + \ldots\}$$
$$= 0{\cdot}182 \text{ second.}$$

* See Greenhill's "Elliptic Functions," p. 19.
† CARR, *loc. cit.*
‡ In this equation ω_0 has the dimensions LT^{-1}.

The curve of current variations corresponding to $\theta = 80°$ is the longest record and from it we see that after the first two or three revolutions, when the motor has settled down, the time of a revolution is 0·25 second. This is the period for a revolution with the motor loaded, whereas the calculation refers to no-load conditions. There is sufficient agreement to show that some idea of the order of the period can be obtained by calculation. This appears to have a very important practical application. Suppose that a synchronous induction motor is working from the same supply as a number of salient-pole synchronous motors or rotary converters. If the load on the motor is increased to such a point that the motor falls out of synchronism and is not immediately disconnected from the system, current surges of definite frequency will be set up. These surges will produce forced oscillations in the other synchronous machines, and if the frequency is of the same order as the natural frequency of oscillation of these machines they will fall out of step. Furthermore, the time required to bring this about may not be more than a few seconds. The property which the synchronous induction motor possesses of continuing to run

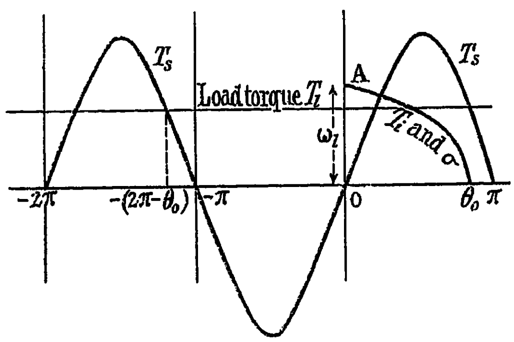

FIG. 12.

under overload conditions may therefore be a disadvantage in such circumstances.

The limiting value of T_m for synchronizing.—The formulæ developed by Carr * and Böhm † are based on the assumption that the work done by what Carr calls the net oscillating torque acting over the angular distance $-(2\pi - \theta_0)$ to $+\theta_0$, i.e. a whole revolution of slip, is equal to the work done in accelerating the moving masses. θ_0 is the angular position of unstable equilibrium with the motor loaded, its position being defined by the intersection in the third quadrant of the curves of T_l and T_s (see Fig. 12).

The synchronizing torque is therefore assumed to exist over the whole of this angular distance, or, in other words, the excitation is assumed to be switched on at the angular position $-(2\pi - \theta_0)$. This method of calculation is based on the worst possible conditions for synchronizing, such conditions never existing in practice because it is not a difficult matter to switch on the excitation in the neighbourhood of the position $\theta = 0$, i.e. the best position for synchronizing. It follows that if the exciter capacity is calculated from the formulæ developed on the above assumption it will be considerably larger than is required in actual practice Again, the formula given by Carr is based on an artificial value for the angular velocity at the position $\theta = 0$. This does not appear to be justifiable, because the angular velocity at the instant of switching on the excitation is the ordinary induction motor slip velocity and is therefore known if the magnitude of the load torque T_l is known. The criterion is the true induction-motor slip angular velocity and not the velocity given by a special solution of the differential equation of motion.

It therefore appears to be more logical to make the calculation on the assumption that the excitation is switched on at the angular position $\theta = 0$, and also to make use of the ordinary slip angular velocity. This method will obviously give the minimum exciter capacity which will enable the motor just to synchronize if the excitation is switched on in the best position.

The slip angular velocity must become zero by the time θ becomes equal to θ_0. Let the slip velocity corresponding to the load T_l be ω_l. Then the slip velocity in electrical radians per second is $p\omega_l$ and the work done in accelerating the moving masses is

$$\tfrac{1}{2} \cdot \frac{I}{p}(p\omega_l)^2$$

The work done against the load torque is obviously $T_l\theta_0$, so that the total work done by the sum of the synchronous and induction-motor torques acting from $\theta = 0$ to $\theta = \theta_0$ is

$$\tfrac{1}{2} \cdot \frac{I}{p}(p\omega_l)^2 + T_l\theta_0$$

When the slip velocity just becomes zero at the position θ_0 the author has found that the slip curve as determined by the step-by-step method is very nearly an ellipse. Since the induction-motor torque is proportional to the slip, this torque can therefore be taken as represented by an ellipse whose semi-axes are θ_0 and T_l. Both synchronizing torque and induction-motor torque are positive over the range considered, so that the work done by the net oscillating torque (assuming the sinusoidal form for T_s) is

$$\int_0^{\theta_0} T_m \sin\theta d\theta + \tfrac{1}{4}\pi T_l\theta_0$$

Hence

$$T_m(1 - \cos\theta_0) + \tfrac{1}{4}\pi T_l\theta_0 = \tfrac{1}{2} \cdot \frac{I}{p}(p\omega_l)^2 + T_l\theta_0$$

Actually the area enclosed by the curve of T_l is rather less than that of a quadrant of an ellipse, so that we can substitute as a fair approximation $\tfrac{3}{4}$ instead of $\tfrac{1}{4}\pi$ for the coefficient of $T_l\theta_0$.* We then have

$$T_m(1 - \cos\theta_0) - 0{\cdot}25T_l\theta_0 = \tfrac{1}{2} \cdot \frac{I}{p}(p\omega_l)^2$$

or $$T_m(1 - \cos\theta_0) - 0{\cdot}25\rho T_m\theta_0 = \tfrac{1}{2} \cdot \frac{I}{p}(p\omega_l)^2$$

* L. H. A. CARR: *Journal I.E.E.*, 1922, vol. 60, p. 165; and 1923, vol. 61, p. 692.
† O. BÖHM: *E.T.Z.*, 1922, vol. 43, p. 429.

* The ratio of the area enclosed by curve A (Fig. 12) to that of a quarter ellipse with equal semi-axes, is almost exactly 3 to π.

Now $\sin\theta_0 = \rho$, and θ_0 is in the second quadrant.

Hence $\qquad \cos\theta_0 = -\sqrt{(1-\rho^2)}$

$$\therefore \quad T_m\{(1+\sqrt{1-\rho^2}) - 0\cdot25\rho\theta_0\} = \tfrac{1}{2}\cdot\frac{\mathrm{I}}{p}(p\omega_l)^2$$

or
$$T_m = \frac{\mathrm{I}p\omega_l^2}{2\{1+\sqrt{(1-\rho^2)} - 0\cdot25\rho\theta_0\}}$$

We see from the form of this expression that since ρ is always less than unity it is quite unnecessary to make any very elaborate calculation in order to determine more exactly the work done by the induction-motor torque.

In the case of the 2-h.p. motor we have $\mathrm{I} = 0\cdot135$; $p = 2$; $\omega_l = 3\cdot98$ radians per sec.; $\rho = 0\cdot286$; and therefore $\theta_0 = 2\cdot85$ radians. Hence the necessary value of T_m for the motor just to synchronize when the excitation is switched on at the most favourable moment is 1·23 lb.-ft. By plotting the slip curves for different assumed values of ρ and using the experimentally determined data it was found that the motor just synchronized for ρ in the neighbourhood of 0·7 when $\theta = +\theta_0$. This is contrary to what actually takes place, because at the moment of switching on the direct-current excitation ω will be equal to ω_l, no matter what the angular position of the rotor may be. The velocity ω_l is a function of ρ, as it should be, but in Mr. Carr's expression the ω used bears no relation to ρ.

Graphical determination of the operation of the motor.—Assuming a sinusoidal form for the synchronizing torque, the equation of slip motion is

$$-\rho T'_m + T_m\sin\theta + \frac{\rho T_m}{p\omega}\cdot\frac{d\theta}{dt} + \frac{\mathrm{I}}{p}\cdot\frac{d^2\theta}{dt^2} = 0$$

or say

$$a + b\sin\theta + c\frac{d\theta}{dt} + d\frac{d^2\theta}{dt^2} = 0$$

For the 2-h.p. motor $a = -\rho = -0\cdot286$; $b = 1\cdot0$ $c = 0\cdot036$; $d = 0\cdot012$. A step-by-step solution was adopted.

Since it was required to determine the positions of switching on the d.c. excitation for which the motor would synchronize under actual working conditions, the

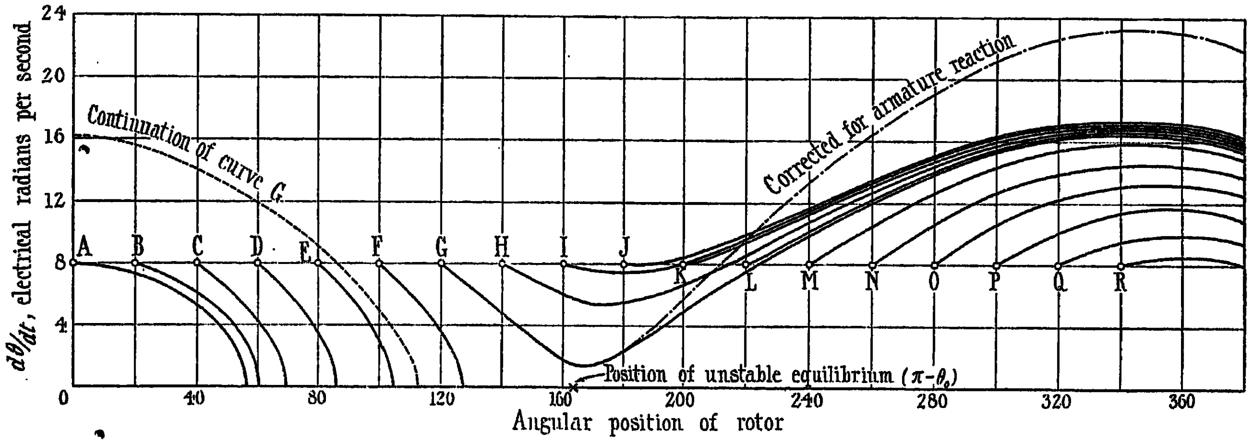

FIG. 13.

the excitation was switched on at the position $\theta = 0$. Using this value of ρ in the above expression for T_m we have

$$\omega_l = 3\cdot98 \times \frac{0\cdot7}{0\cdot286} = 9\cdot7$$

Therefore $\qquad \theta_0 = 2\cdot37$ radians.

Hence $\qquad T'_m = 8\cdot0$ lb.-ft.

This is as near to the actual value of 6·04 lb.-ft. as can reasonably be expected for such a small motor. Since the above method of determining T_m gives the least value for which it is possible for the motor to synchronize, even under the most favourable conditions of switching in, while the methods of other investigations give the maximum value of T_m required for the worst conditions, a good value of the necessary exciter capacity is obtained from these two extreme cases.

There is one other criticism of Mr. Carr's method of calculating the limiting value of T_m, i.e. in determining the value of ω used in his expression the angular velocity is assumed to be zero both at $\theta = -(2\pi - \theta_0)$ and at experimentally determined values of ρ and ω (the initial slip) were used. The curves obtained are shown in Fig. 13. It will be noticed that each curve has an initial ordinate of 7·96 electrical radians per second and that the commencing points A, B, C, D, etc., correspond to the angular positions of the rotor, 0°, 20°, 40°, 60°, etc., at which the d.c. excitation was switched on. The effect of the synchronizing torque immediately after switching on is very clearly indicated by the initial gradients of the various curves. With $\theta = 0$ the initial component $T'_m\sin\theta$ of the synchronizing torque is zero, the curve therefore being at first horizontal. As θ is increased up to 90°, $T_m\sin\theta$ increases and is in a direction opposed to the slip, the curves therefore having a gradually increasing initial negative gradient. From 90° to 180° this initial gradient gradually reduces to zero again. Similar changes in initial gradient occur for the various switching positions between 180° and 360°, except that in this case $T_m\sin\theta$ is negative, i.e. in the same direction as the slip, the initial gradients therefore being positive.

According to the curves the angular velocity for

switching positions of 0°, 20°, 40°, 60°, 80° and 100° becomes zero before the displacement attains that corresponding to unstable equilibrium, 163·5° in this case. Hence the motor should synchronize. When switching-in occurs at 120° the motor just fails to synchronize in the first swing, the rotor therefore passing the critical position of 163·5° with gradually increasing velocity. In order to cut down the tedious step-by-step method of calculation to a minimum, a value of the initial slip when passing the position $\theta = 0$ was found for which the motor would just synchronize, i.e. for which the angular velocity at $\theta = 163 \cdot 5°$ was zero. This was 19·97 electrical radians per second. Knowing this critical value at $\theta = 0°$ (or $n \times 360°$) it is only necessary to calculate the various curves as far as the position $\theta = 360°$. If the angular velocity at 360° is less than this critical value, the motor will synchronize; if greater it will not synchronize. It will be seen from the curves that in every case the angular velocity at 360° is less than 19·97 electrical radians, from which if follows that the motor should synchronize no matter where the excitation is switched on. This is, of course, contrary to the experimental evidence and shows very conclusively that the generally accepted equation of motion is not correct. In Fig. 13 the curve corresponding to the switching position $\theta = 120°$ is continued as a dotted line beyond the position $\theta = 360°$.

Comparing the theoretical with the actual behaviour of the motor, we see that the conditions for synchronizing in the actual case are much more severe than in the theoretical case. The difference is undoubtedly due to the effect of armature reaction on the form of the synchronizing torque. It will be seen from Fig. 13 that the most important curve in the family is that corresponding to the switching-on of the excitation when $\theta = 120°$, since this curve very nearly meets the θ axis at the position of unstable equilibrium. This curve has therefore been re-drawn, as shown by the chain-dotted curve, on the assumption that the synchronizing torque is modified by armature reaction so that it varies with θ as indicated by Fig. 7. Up to $\theta = 180°$ there is very little difference between this curve and the original curve G, but beyond 180° the new curve rises very rapidly, the angular velocity at $\theta = 360°$ being now 23 electrical radians per second. It was found by trial and error that the maximum possible velocity at $\theta = 0$ (or $n \times 360°$) for the motor just to synchronize was 19·97. This shows that the effect of armature reaction is sufficient to explain the difference between the actual behaviour and the theoretical behaviour on the assumption that the synchronizing torque is a sinusoidal function of θ. The same correction applied to the group of curves G, H, I, J, K and L, brings them also above the critical value of 19·97 at $\theta = 360°$, thus bringing the theoretically determined operation of the motor into reasonably close agreement with the actual performance on test.

Conclusion.

The comparison of the theoretical and experimental investigations indicates that the conditions of operation of a synchronized induction motor during the process of pulling into synchronism are much more severe than they are generally taken to be. Owing to the magnetic weakness of the rotor and the very small air-gap used, the effect of armature reaction is enormously greater than in the case of the salient-pole synchronous motor. It is probable that in a commercial motor the effect will not be so great as in the small motor used in the experimental work, because the excitation was purposely kept at a low value throughout. This naturally gave a very weak field, the result being an exaggerated distortion of the curve of synchronizing torque. In an actual case the distortion will undoubtedly be considerably less than that indicated by Fig. 7, but it is obvious that it will still be of sufficient importance to justify the use of the more accurate formula for the synchronizing torque when investigating slip motions extending into the generating region. This does not introduce any extra work in the step-by-step calculation, since, if the curve of synchronizing torque is drawn, the mean value corresponding to the steps used can be calculated by Simpson's rule from three ordinates read off directly.

The difficulties encountered in the experimental investigation of the slip motion illustrate very forcibly that for work of this nature the speed indicator used must be rigidly attached to the motor shaft, and that even a very stiff spring coupling is not permissible. The simple disc and magnet dynamo is absolutely accurate and the small voltage corresponding to the slip can be magnified to any desired extent by means of a thermionic valve of sufficient capacity. As pointed out previously, the use of a speed indicator of this kind does not necessitate the exciter being deprived of its proper function. The result of this is that the record of speed variations as obtained by experiment will be a true reproduction of the variations that take place under actual working conditions.

Case of the Salient-pole Synchronous Motor.

The behaviour of this motor during the process of synchronizing is somewhat different from that of the non-salient-pole type, owing to the fact that the synchronizing torque now possesses two components. The first component is that due to the flux produced by the d.c. excitation of the rotor, or, in the case of a rotary converter, of the stator. This can be represented as before by the expression $T_m \sin \theta$. If the excitation is zero during starting, this component will be set up by residual magnetism, and in such a case T_m will of necessity be very small. Secondly there is a torque set up by the flux induced in the salient poles by the synchronously rotating field will induce opposite polarity in each of the salient poles in turn, no matter what the ultimate polarity of those salient poles has to be. This torque is an alternating function of the angle θ and we see from the manner in which it is produced that its frequency must be twice that of the component $T_m \sin \theta$. Also it is zero when θ is zero. It can therefore be represented by an expression of the form $T_m \sin 2\theta$. The assumption of a sinusoidal function is only approximate for this component as it is for the other, but an experiment showed that the departure from the true sinusoidal form is not very great.

The results of this experiment are given in Fig. 14, and the sin 2θ curve is drawn for comparison. It will be seen that the curve does not differ greatly from a sine curve. The equation of slip motion of a salient-pole motor can be written thus :—

$$-\rho T_m + T_m \sin\theta + \xi T_m \sin 2\theta + \frac{\rho T_m}{p\omega}\cdot\frac{d\theta}{dt} + \frac{\mathrm{I}}{p}\cdot\frac{d^2\theta}{dt^2} = 0$$

where ξ is a constant depending upon the degree of excitation of the salient poles.

If the angular velocity of phase swing is required for the case of a salient-pole machine, this can be determined for the no-load case by transforming the equation of motion as follows. Put $\rho = 0$, multiply by $2d\theta/dt$ and integrate with respect to t. Let $\theta = \theta_0$ when $d\theta/dt = 0$. Then

$$2T_m(\cos\theta_0 - \cos\theta) + \xi T_m(\cos 2\theta_0 - \cos 2\theta) + \frac{\mathrm{I}}{p}\left(\frac{d\theta}{dt}\right)^2 = 0$$

$$\therefore\quad \frac{d\theta}{dt} = 2\sqrt{\left[\frac{T_m p}{\mathrm{I}}\right]}$$

$$\times\{(\sin^2\tfrac{1}{2}\theta_0 - \sin^2\tfrac{1}{2}\theta)(1+2\xi-2\xi\sin^2\tfrac{1}{2}\theta_0 - 2\xi\sin^2\tfrac{1}{2}\theta)\}^{\frac{1}{2}}$$

This enables the calculation to be made for the maximum allowable value of the slip for which the motor will

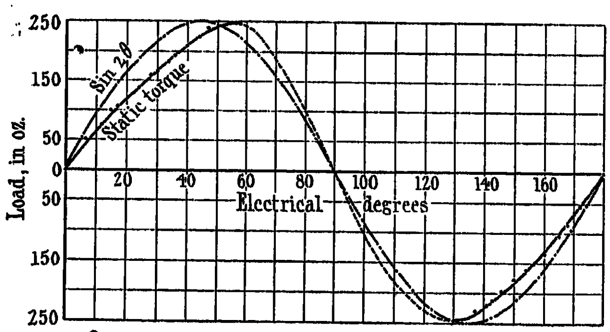

Fig. 14.

just synchronize. For values of $\xi \not> \frac{1}{2}$ the author has shown * that the conditions for a salient-pole motor are the same as for a non-salient-pole motor. Thus if the excitation is switched on at the instant $\theta = 0$, the above equation gives for the maximum allowable value of the slip

$$\left(\frac{d\theta}{dt}\right)_{\theta=0} = 2\sqrt{\left[\frac{T_m p}{\mathrm{I}}\right]}\ \dagger$$

When $\xi > \frac{1}{2}$ the expression for the critical angular velocity is of the form

$$\left(\frac{d\theta}{dt}\right)_{\theta=0} = f(\xi) \times \sqrt{\left[\frac{T_m p}{\mathrm{I}}\right]}$$

It is possible to determine the nature of $f(\xi)$ in the general case by making the assumption that the mean decrease of slip as θ varies from zero to θ_0 is equal to one-half of the total decrease. The error introduced by this assumption is not great, being less than the error introduced when it is assumed that the mean value of a sinusoidal function is one-half of the maximum value. The positions of equilibrium are given by the equation

$$\sin\theta + \xi\sin 2\theta = 0$$

$$\therefore\quad \sin\theta(1 + 2\xi\cos\theta) = 0$$

Putting $\sin\theta = 0$ we have $\theta = 0$, π, or 2π, and these values apply to the case in which $\xi < \frac{1}{2}$.

Putting $(1 + 2\xi\cos\theta) = 0$

we have

$$\theta = \text{arc cos}\left(-\frac{1}{2\xi}\right) \quad\text{or}\quad 2\pi - \text{arc cos}\left(-\frac{1}{2\xi}\right)$$

and these values apply to the case in which $\xi > \frac{1}{2}$. Let us consider that the slip at $\theta = 0$ is such that the system is just brought to rest at the first unstable position defined by

$$\theta = \text{arc cos}\left(-\frac{1}{2\xi}\right)$$

Putting $\omega = d\theta/dt$ we have for the equation of motion

$$\frac{\mathrm{I}}{p}\cdot\frac{d\omega}{dt} = -T_m\sin\omega t - \xi T_m \sin 2\omega t$$

Let $\delta\omega$ be the mean decrease in ω over the interval we are considering, then the mean value of the slip speed will be $(\omega - \delta\omega)$. Hence the time taken to travel from the position $\theta = 0$ to $\theta = \text{arc cos}\left(-\frac{1}{2\xi}\right)$ is

$$\frac{\text{arc cos}\left(-\frac{1}{2\xi}\right)}{\omega - \delta\omega}$$

We therefore have for the total decrease in slip during this interval

$$\frac{T_m p}{\mathrm{I}}\int_0^{\text{arc cos}\left(-\frac{1}{2\xi}\right)/(\omega-\delta\omega)} \sin(\omega-\delta\omega)t\,dt + \frac{\xi T_m p}{\mathrm{I}}\int_0^{\text{arc cos}\left(-\frac{1}{2\xi}\right)/(\omega-\delta\omega)} \sin 2(\omega-\delta\omega)t\,dt$$

$$= -\frac{T_m p}{\mathrm{I}}\times\frac{1}{\omega-\delta\omega}\Big[\cos(\omega-\delta\omega)t\Big]_0^{\text{arc cos}\left(-\frac{1}{2\xi}\right)/(\omega-\delta\omega)}$$

$$-\frac{\xi T_m p}{\mathrm{I}}\times\frac{1}{2(\omega-\delta\omega)}\Big[\cos 2(\omega-\delta)t\Big]_0^{\text{arc cos}\left(-\frac{1}{2\xi}\right)/(\omega-\delta\omega)}$$

$$= \frac{T_m p}{\mathrm{I}}\times\frac{1}{\omega-\delta\omega}\left(1+\frac{1}{2\xi}\right) + \frac{\xi T_m p}{\mathrm{I}}\times\frac{1}{2(\omega-\delta\omega)}\left(2-\frac{1}{2\xi^2}\right)$$

$$= \frac{T_m p}{\mathrm{I}}\times\frac{1}{\omega-\delta\omega}\left(1+\frac{1}{4\xi}+\xi\right)$$

$$= \frac{\xi T_m p}{\mathrm{I}}\times\frac{1}{\omega-\delta\omega}\left(1+\frac{1}{2\xi}\right)^2$$

But the total decrease in slip must be equal to ω, the angular velocity as the system is passing the lowest

* *Electrician*, 1924, vol. 92, p. 220.
† Also see L. H. A. Carr, *loc. cit.*, p. 696.

point, and therefore we have finally, making the above-mentioned assumption of $\omega = 2\delta\omega$:—

$$\omega_{\theta=0} = \left(\frac{d\theta}{dt}\right)_{\theta=0} = \sqrt{(2\xi)}\left(1 + \frac{1}{2\xi}\right)\sqrt{(T_m p/\mathrm{I})}$$

$$= \sqrt{\left(2 + 2\xi + \frac{1}{2\xi}\right)}\sqrt{(T_m p/\mathrm{I})}$$

Hence $$f(\xi) = \sqrt{\left(2 + 2\xi + \frac{1}{2\xi}\right)}$$

An expression for the time of one complete oscillation of phase swing can be determined as follows. First take the case of a non-salient-pole machine. We have :—

$$T_m \sin\theta + \frac{\mathrm{I}}{p}\cdot\frac{d^2\theta}{dt^2} = 0$$

$$\therefore \left(\frac{d\theta}{dt}\right)^2 = 2\frac{T_m p}{\mathrm{I}}\cos\theta + K$$

If $d\theta/dt = 0$ when $\theta = \alpha$, where α is an angle less than θ_0, the position of unstable equilibrium, then

$$\frac{d\theta}{dt} = 2\sqrt{\left[\frac{T_m p}{\mathrm{I}}\right]}(\sin^2\tfrac{1}{2}\alpha - \sin^2\tfrac{1}{2}\theta)^{\frac{1}{2}}$$

$$\therefore \frac{dt}{d\theta} = \tfrac{1}{2}\sqrt{\left[\frac{\mathrm{I}}{T_m p}\right]} \times \frac{1}{(\sin^2\tfrac{1}{2}\alpha - \sin^2\tfrac{1}{2}\theta)^{\frac{1}{2}}}$$

Hence the period of phase swing

$$P = 2\sqrt{\left[\frac{\mathrm{I}}{T_m p}\right]}\int_0^{\alpha}\frac{d\theta}{(\sin^2\tfrac{1}{2}\alpha - \sin^2\tfrac{1}{2}\theta)^{\frac{1}{2}}}$$

Putting $$\sin\tfrac{1}{2}\theta = \sin\tfrac{1}{2}\alpha\sin\phi$$

this reduces to the standard form of elliptic integrals, namely

$$P = 2\sqrt{\left[\frac{\mathrm{I}}{T_m p}\right]}\int_0^{\frac{1}{2}\pi}\frac{d\phi}{\sqrt{(1 - \sin^2\tfrac{1}{2}\alpha\sin^2\phi)}}$$

$$= 2\pi\sqrt{\left[\frac{\mathrm{I}}{T_m p}\right]} \times \frac{1}{\pi}\int_0^{\frac{1}{2}\pi}\frac{d\phi}{\sqrt{(1 - \sin^2\tfrac{1}{2}\alpha\sin^2\phi)}}$$

Values of $$\frac{1}{\pi}\int_0^{\frac{1}{2}\pi}\frac{d\phi}{\sqrt{(1 - \sin^2\tfrac{1}{2}\alpha\sin^2\phi)}}$$

have been tabulated for different values of α. In the particular case in which α is equal to π the period is theoretically infinite.

In the case of the salient-pole motor we have :—

$$\sqrt{\left[\frac{T_m p}{\mathrm{I}}\right]}\{(\sin^2\tfrac{1}{2}\alpha - \sin^2\tfrac{1}{2}\theta)(1 + 2\xi - 2\xi\sin^2\tfrac{1}{2}\theta - 2\xi\sin^2\alpha)\}^{\frac{1}{2}}$$

If the extent of the swing is such that $\alpha = \theta_0$, the position of unstable equilibrium, then

$$\frac{d\theta}{dt} = 2\sqrt{\left[\frac{T_m p}{\mathrm{I}}\right]}\sqrt{(2\xi)}\,(\sin^2\tfrac{1}{2}\theta_0 - \sin^2\tfrac{1}{2}\theta)$$

$$dt = \tfrac{1}{2}\sqrt{\left[\frac{\mathrm{I}}{T_m p}\right]} \times \frac{1}{\sqrt{(2\xi)}} \times \frac{d\theta}{(\sin^2\tfrac{1}{2}\theta_0 - \sin^2\tfrac{1}{2}\theta)}$$

and for the period we have

$$P = \frac{2}{\sqrt{(2\xi)}}\cdot\sqrt{\left[\frac{\mathrm{I}}{T_m p}\right]}\int_0^{\theta_0}\frac{d\theta}{\sin^2\tfrac{1}{2}\theta_0 - \sin^2\tfrac{1}{2}\theta}$$

This is equal to ∞, as would be expected from the analogy of the non-salient-pole motor with an amplitude of phase-swing of 2π radians.*

If $\alpha < \theta_0$ then

$$\frac{dt}{d\theta} = \tfrac{1}{2}\sqrt{\left[\frac{\mathrm{I}}{T_m p}\right]}$$

$$\frac{1}{\{(\sin^2\tfrac{1}{2}\alpha - \sin^2\tfrac{1}{2}\theta)(1+2\xi-2\xi\sin^2\tfrac{1}{2}\theta-2\xi\sin^2\tfrac{1}{2}\alpha)\}^{\frac{1}{2}}}$$

and

$$P = 2\sqrt{\left[\frac{\mathrm{I}}{T_m p}\right]}$$

$$\int_0^{\alpha}\frac{d\theta}{\{(\sin^2\tfrac{1}{2}\alpha - \sin^2\tfrac{1}{2}\theta)(1+2\xi-2\xi\sin^2\tfrac{1}{2}\theta-2\xi\sin^2\tfrac{1}{2}\alpha)\}^{\frac{1}{2}}}$$

This integral does not appear to be amenable to solution, even by the use of elliptic integrals.† Some idea of the period of oscillation can be obtained from the following treatment of the problem. Let the line of centres of the two weighted discs whose motion is a reproduction of the slip motion ‡ be horizontal. Then the height of the centre of gravity of the system above the line of centres is

$$\frac{-\cos\theta - \xi \times \tfrac{1}{2}\cos 2\theta}{1 + \xi}$$

Hence if z is the height of the centre of gravity of the system above the lowest possible position (given by $\theta = 0$), we have :—

$$z = \frac{1 - \cos\theta + \tfrac{1}{2}\xi(1 - \cos 2\theta)}{1 + \xi}$$

$$= \frac{1}{1 + \xi}(1 + \xi - \cos\theta - \xi\cos^2\theta)$$

$$\frac{dz}{d\theta} = \frac{\sin\theta}{1 + \xi}(1 + 2\xi\cos\theta)$$

$$= \frac{2\xi}{1 + \xi}\sin\theta\left\{\cos\theta - \left(-\frac{1}{2\xi}\right)\right\}$$

Case (1). $\xi < \tfrac{1}{2}$ $\therefore$ $\dfrac{1}{2\xi} > 1$.—$dz/d\theta = 0$ only if

* The integration is given in Appendix 1.
† An integration in terms of a converging series is given in Appendix 2.
‡ H. Cotton, *loc. cit.*

$\sin\theta = 0$, i.e. if $\theta = 0$ or $n\pi$, where n is a positive or negative integer.

$\theta = 0$ gives a minimum,
$\theta = \pi$ gives a maximum,
$\theta = 2\pi$ gives a minimum, and so on.

If $\theta = 0$; $z = 0$, the minimum value.

If $\theta = \pi$; $z = \dfrac{2}{1+\xi}$, the maximum value.

The variation of z with θ is shown in Fig. 15.

Case (2). $\xi > \frac{1}{2}$ $\therefore$ $\dfrac{1}{2\xi} < 1$.—$dz/d\theta = 0$ for $\theta = 0$ or $n\pi$ as before, but also for

$$\theta = \text{arc}\cos\left(-\frac{1}{2\xi}\right), \text{ or } \theta = \pi - \text{arc}\cos\left(-\frac{1}{2\xi}\right),$$
$$\text{or } \theta = \pi + \text{arc}\cos\left(-\frac{1}{2\xi}\right),$$

taking only values of θ between 0 and 2π.

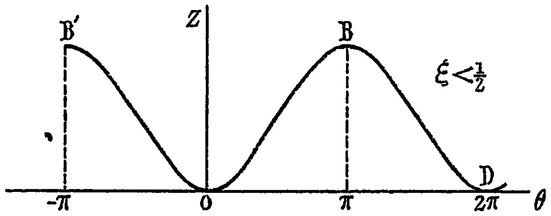

FIG. 15.

Now maxima and minima occur alternately, and $\theta = 0$ obviously gives a minimum.
Hence

$\theta = 0$ gives the minimum value $z = 0$

$\theta = \pi - \text{arc}\cos\left(-\dfrac{1}{2\xi}\right)$ gives a maximum value

$$z = \frac{1}{1+\xi}(1 + \xi - \cos\theta - \xi\cos^2\theta)$$
$$= \frac{1}{1+\xi}\left(1 + \xi + \frac{1}{2\xi} - \frac{\xi}{4\xi^2}\right)$$
$$= 1 + \frac{1}{4\xi(1+\xi)}$$

$\theta = \pi$ gives a minimum value $z = \dfrac{2}{1+\xi}$

$\theta = \pi + \text{arc}\cos\left(-\dfrac{1}{2\xi}\right)$ gives a maximum value

$$z = \frac{1}{1+\xi}(1 + \xi - \cos\theta - \xi\cos^2\theta)$$
$$= 1 + \frac{1}{4\xi(1+\xi)} \text{ as for } \theta = \pi - \text{arc}\cos\left(-\frac{1}{2\xi}\right)$$

$\theta = 2\pi$ gives the minimum value $z = 0$, as for $\theta = 0$.
The variation of z with θ is shown in Fig. 16.

Consider now the dynamical aspect of the problem. If the moments of inertia of the two discs A and B, including their added weights, are $\mathbf{I}_1$ and $\mathbf{I}_2$ respectively, then the rotational energy of the system is

$$\tfrac{1}{2}\mathbf{I}_1\left(\frac{d\theta}{dt}\right)^2 + \tfrac{1}{2}\mathbf{I}_2\left(2\frac{d\theta}{dt}\right)^2$$

$= \frac{1}{2}\dot{\theta}(\mathbf{I}_1 + 4\mathbf{I}_2)$ [using the notation $D'(\theta) = \dot{\theta}$]

Replace $(\mathbf{I}_1 + 4\mathbf{I}_2)$ by $\mathbf{I}/p$ and let the weights in absolute units (i.e. including g) be T_m and ξT_m.

Then by the principle of the conservation of energy, if $\dot{\theta} = \omega$ when $\theta = 0$ we have :—

$$\tfrac{1}{2}\cdot\frac{\mathbf{I}}{p}(\dot{\theta}^2 - \omega^2) + T_m(1 - \cos\theta) + \xi T_m\cdot\tfrac{1}{2}(1 - \cos 2\theta) = 0$$

This is the integrated form of the equation of motion for no-load conditions, namely :—

$$\frac{\mathbf{I}}{p}\ddot{\theta} + T_m\sin\theta + \xi T_m\sin 2\theta = 0$$

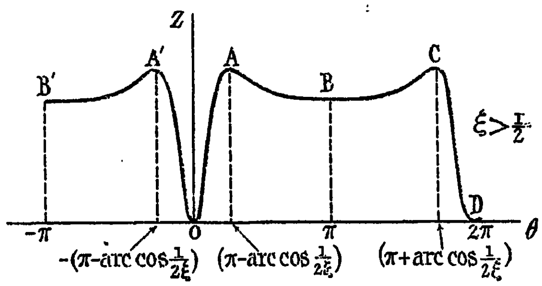

FIG. 16.

Substituting the previously obtained expression for z we have

$$\tfrac{1}{2}\cdot\frac{\mathbf{I}}{p}(\dot{\theta}^2 - \omega^2) + T_m(1 + \xi)z = 0$$
$$\therefore\quad \dot{\theta}^2 = \omega^2 - \frac{2pT_m}{\mathbf{I}}(1 + \xi)z$$

Hence

$$\dot{\theta} = 0 \text{ if } \omega = \sqrt{\left[\frac{2pT_m}{\mathbf{I}}(1 + \xi)z\right]}$$

Case (1) $\xi < \frac{1}{2}$.—For complete revolutions the system has to get past the point B (Fig. 15) for which $z_B = 2/(1 + \xi)$

$$\therefore\quad \omega > 2\sqrt{\left[\frac{T_m p}{\mathbf{I}}\right]}$$
$$> \omega_1, \text{ say.}$$

If $\omega < \omega_1$ the system will oscillate between $\pm\alpha$ where $\alpha < \pi$, and the period can be calculated exactly by means of elliptic functions.

Case (2) $\xi > \frac{1}{2}$.—For complete revolutions the system has to get past the angular positions A and C (Fig. 16) for which $z_A = z_C = 1 + 1/[4\xi(1 + \xi)]$

Hence

$$\omega > \sqrt{\frac{T_m p}{\mathbf{I}}\left(2 + 2\xi + \frac{1}{2\xi}\right)}$$
$$> \sqrt{2\xi}\left(1 + \frac{1}{2\xi}\right)\sqrt{\left[\frac{T_m p}{\mathbf{I}}\right]} > \omega_2, \text{ say.}$$

This gives the same form of $f(\xi)$ as the integration on page 225. If $\omega < \omega_2$ the system will oscillate between $\pm\beta$, where $\beta < \pi - \text{arc cos}\,[-1/(2\xi)]$.

If there is some friction, as of course there is in a practical case,* and ω is only a little greater than ω_2 initially, the system might oscillate somewhere between the positions corresponding to the points A and C, or to similar positions later on.

We can obtain some measure of the time of revolution (for complete revolutions) as follows.

$\dot{\theta}$ has a maximum value of ω, and a minimum value of ω_1 when $\xi < \frac{1}{2}$.

Hence

$$P < \frac{2\pi}{\omega} \quad \text{and} \quad > \frac{2\pi}{\sqrt{(\omega^2 - \omega_1^2)}}$$

$\dot{\theta}$ has a maximum value of ω and a minimum value of ω_2 when $\xi > \frac{1}{2}$.

Hence

$$P < \frac{2\pi}{\omega} \quad \text{and} \quad > \frac{2\pi}{\sqrt{(\omega^2 - \omega_2^2)}}$$

APPENDIX 1.

$$\int_0^{\theta_0} \frac{d\theta}{\sin^2 \frac{1}{2}\theta_0 - \sin^2 \frac{1}{2}\theta} = \int_0^{\theta_0} \frac{\sec^2 \frac{1}{2}\theta\, d\theta}{\sin^2 \frac{1}{2}\theta_0 \sec^2 \frac{1}{2}\theta - \tan^2 \frac{1}{2}\theta}$$

$$= \int_0^{t_0} \frac{2dt}{(1 + t^2)\sin^2 \frac{1}{2}\theta_0 - t^2}$$

where $t = \tan \frac{1}{2}\theta$, $t_0 = \tan \frac{1}{2}\theta_0$

$$= \int_0^{t_0} \frac{2dt}{\sin^2 \frac{1}{2}\theta_0 - t^2 \cos^2 \frac{1}{2}\theta_0}$$

$$= \frac{1}{\cos^2 \frac{1}{2}\theta_0} \int_0^{t_0} \frac{2dt}{t_0^2 - t^2}$$

$$= \frac{1 + t_0^2}{t_0} \int_0^{t_0} \left(\frac{1}{t_0 + t} + \frac{1}{t_0 - t}\right) dt$$

$$= \frac{1 + t_0^2}{t_0} \left(\log \frac{2t_0}{0} - \log \frac{t_0}{t_0}\right)$$

$$= \infty$$

APPENDIX 2.

We have :—

$$\frac{d\theta}{dt} = 2\sqrt{\left[\frac{T_m p}{\mathrm{I}}\right]} \times \{(\sin^2 \tfrac{1}{2}\alpha - \sin^2 \tfrac{1}{2}\theta)(1 + 2\xi - 2\xi \sin^2 \tfrac{1}{2}\alpha - 2\xi \sin^2 \tfrac{1}{2}\theta)\}$$

where $0 = \alpha$ when $d\theta/dt = 0$ and $\xi > \frac{1}{2}$.

$$\therefore \frac{d\theta}{dt} = 2\sqrt{\left[\frac{T_m p}{\mathrm{I}}\right]} \times \sqrt{(2\xi)}\{(\sin^2 \tfrac{1}{2}\alpha - \sin^2 \tfrac{1}{2}\theta)(a - \sin^2 \tfrac{1}{2}\theta)\}^{\frac{1}{2}}$$

where $a = \dfrac{1}{2\xi} + 1 - \sin^2 \frac{1}{2}\alpha$

Hence the period in seconds

$$P = 2\sqrt{\left[\frac{\mathrm{I}}{T_m p}\right]} \times \frac{1}{\sqrt{(2\xi)}} \int_0^{\alpha} \frac{d\theta}{\sqrt{[(\sin^2 \frac{1}{2}\alpha - \sin^2 \frac{1}{2}\theta)(a - \sin^2 \frac{1}{2}\theta)]}}$$

In order that the integration may be possible it is obvious that we must have $a > \sin^2 \frac{1}{2}\alpha$, otherwise the function would become infinite and then imaginary before θ attained the value α. This condition is fulfilled because $\alpha > \theta_0$, where $\theta_0 = \text{arc cos}\,[-1/(2\xi)]$.

Substituting $\sin \frac{1}{2}\theta = \sin \frac{1}{2}\alpha \sin \phi$

we have $\phi = 0$ when $\theta = 0$
and $\phi = \frac{1}{2}\pi$ when $\theta = \alpha$

Hence

$$P = 2\sqrt{\left[\frac{\mathrm{I}}{T_m p}\right]} \times \frac{1}{\sqrt{(2\xi)}} \int_0^{\frac{1}{2}\pi} \frac{d\phi}{\sqrt{(1 - \sin^2 \frac{1}{2}\alpha \sin^2 \phi)}\sqrt{a}\sqrt{\left(1 - \frac{1}{a}\sin^2 \frac{1}{2}\alpha \sin^2 \phi\right)}}$$

$$= 2\sqrt{\left[\frac{\mathrm{I}}{T_m p}\right]} \times \frac{1}{\sqrt{(2a\xi)}} \int_0^{\frac{1}{2}\pi} (1 - m^2 \sin^2 \phi)^{-\frac{1}{2}} (1 - n^2 \sin^2 \phi)^{-\frac{1}{2}} d\phi$$

where $m^2 = \sin^2 \frac{1}{2}\alpha$, $n^2 = \dfrac{1}{a}\sin^2 \frac{1}{2}\alpha$

Either bracket expanded alone gives a converging series. Hence expanding and collecting similar terms we have :—

$$P = 2\sqrt{\left[\frac{\mathrm{I}}{T_m p}\right]} \times \frac{1}{\sqrt{(2a\xi)}} \int_0^{\frac{1}{2}\pi} [1 + (\tfrac{1}{2} + \tfrac{1}{2}k)m^2 \sin^2 \phi + (\tfrac{3}{8} + \tfrac{1}{4}k + \tfrac{3}{8}k^2)m^4 \sin^4 \phi + (\tfrac{5}{16} + \tfrac{3}{16}k + \tfrac{3}{16}k^2 + \tfrac{5}{16}k^3)m^6 \sin^6 \phi + \ldots] d\phi$$

where $k = 1/a$

$$\therefore P = \pi\sqrt{\left[\frac{\mathrm{I}}{T_m p}\right]} \times \frac{1}{\sqrt{(2a\xi)}} \left[1 + \tfrac{1}{2}(\tfrac{1}{2} + \tfrac{1}{2}k)\sin^2 \tfrac{1}{2}\alpha + \frac{3 \,.\, 1}{4 \,.\, 2}(\tfrac{3}{8} + \tfrac{1}{4}k + \tfrac{3}{8}k^2)\sin^4 \tfrac{1}{2}\alpha + \frac{5 \,.\, 3 \,.\, 1}{6 \,.\, 4 \,.\, 2}(\tfrac{5}{16} + \tfrac{3}{16}k + \tfrac{3}{16}k^2 + \tfrac{5}{16}k^3)\sin^6 \tfrac{1}{2}\alpha\right]$$

From this expression the period P can be calculated for any value of ξ and for any amplitude α. For the case in which $\xi = 1$ the function in the brackets is

remembered that the motion of the mechanical model is a he slip motion, not the actual motion of the motor. Thus an will cause an increase in the angular velocity of the model, use a decrease in the velocity of the motor.

plotted in Fig. 17. The range of a is from 0 to $\theta_0 (= \text{arc cos } \frac{1}{2})$, the function becoming infinite at this latter value.

When a is small the expression for the period reduces to

$$P = \pi\sqrt{\left[\frac{I}{T'_m p}\right]} \times \frac{1}{\sqrt{(2a\xi)}}\left\{1 + \frac{a^2}{8}\left(\tfrac{1}{2} + \tfrac{1}{2}k\right)\right\}$$

In the figure the elliptic integral $\frac{2}{\pi}F_1(K)$ is plotted for comparison, the scale of a being so modified that both functions become infinite at the same point.

For values of α which make $\sin^2 \frac{1}{2}\alpha < 1/(2\xi)$, $k < 1$. The series is therefore rapidly convergent and, as can be seen from the figure, the curve lies below that of the elliptic integral.

When $\sin^2 \frac{1}{2}\alpha = 1(2\xi)$, $k = 1$. The series is, in consequence, much more slowly convergent because, in addition to the greater importance of the $\sin^n \frac{1}{2}\alpha$

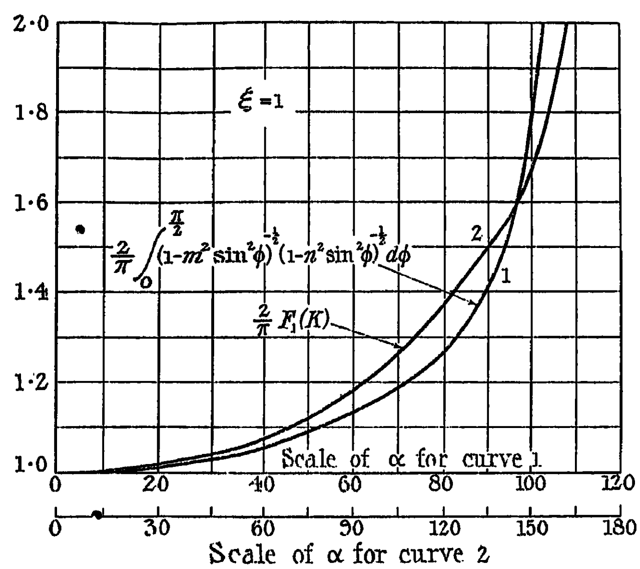

Fig. 17.

coefficients, k raised to increasing powers does not decrease. For $\xi = 1$ this angle is given by

$$\sin^2 \tfrac{1}{2}\alpha = \tfrac{1}{2} \quad \text{or} \quad \alpha = 90°.$$

When $\sin^2 \frac{1}{2}\alpha > \frac{1}{2\xi}$, $k > 1$. The series then converges very slowly and the curve rises very steeply as shown in Fig. 16.

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SARTORI, G.: "A New Compensated Type of Auto-synchronous Motor," *Elettrotecnica*, 1922, vol. 9, pp. 565 and 567.

SWEDISH.

"Autosynchronous Motors" (A.S.E.A. Publication).

The following articles deal specifically with salient-pole machines:—

HAY, A., and MOWDAWALLA, F. N.: "Starting Conditions of Synchronous Machines," *Journal of the American Institute of Electrical Engineers*, 1920, vol. 39, p. 34.

HILLEBRAND, F.: "The Auto-synchronous Starting of Synchronous Motors" (A.E.G. Publication).

SHAND, E. B.: "Starting Characteristics of Synchronous Motors," *Electric Journal*, 1921, vol. 18, p. 309.

BRITISH PATENT SPECIFICATIONS.

24837. Hunt and Sandicroft and Co.—Refers to cascade synchronous induction motors and patents an automatic device for switching on the excitation at the correct instant.

11298. Fynn.—Patents connections for self-excitation.

131812. Burge and Crompton and Co.—Special method of using a two-phase rotor to obtain uniform heating.

158373. Ayres and Metropolitan-Vickers Co.—Patents a method of series-parallel starting.

151269, 169953, 169954. General Electric Co. of France.—Patents a starter.

170824.—General Electric Co. of France.—Patents a special starter which short-circuits one rotor phase, this then acting as a damper.

171412. Siemens-Schuckert Co.—A salient-pole motor with auxiliary windings in the pole-face for starting.

172603. Yamamoto and Kawarada.—Patent referring to connections with exciter permanently in circuit.

180142. Ayres.—Patents special connections for starting.

190521. Whitmore and Lancashire Dynamo Co.—Method of supporting rotor windings.

196391. Carr and Metropolitan-Vickers Co.—Damping circuits.

205627. Hunt and Sandicroft Co.—Special connections for the cascade synchronous induction motor.

The author wishes to thank Mr. L. H. A. Carr for indicating several articles on the synchronous induction motor which he would not otherwise have consulted.

DISCUSSION ON "AN ELECTRIC HARMONIC ANALYSER."*

SCOTTISH CENTRE, AT GLASGOW, 9 DECEMBER, 1924.

Professor G. W. O. Howe: In watching the experimental demonstration † I was very much impressed with the number of adjustments that have to be kept accurate, and the general complication of the measurement compared with many electrical measurements. In estimating these, however, one must take into account the complication of the problem being tackled and compare it with other methods of obtaining the same result. What other methods are there of obtaining this result? The classical method is simply to take an oscillogram, enlarge the curve and then laboriously analyse it. This method certainly gives results, but what these will be worth when one reaches the 13th, 15th and 19th harmonics is, I am afraid, a matter of very great doubt. With an oscillograph, an expert of many years' experience can get tolerably accurate results, but the results obtained by those who have not had such experience often leave very much to be desired with regard to accuracy, especially when the results are afterwards subjected to enlargement and mathematical analysis. In the bibliography at the end of the paper the authors mention a paper of mine on the "Amplitude and Phase of Higher Harmonics in Oscillograms," in which I went into the subject of the accuracy with which the oscillograph reproduces these higher harmonics. As the frequency increases and approaches the natural frequency of the oscillograph, the truthfulness of the representation of the harmonics gradually decreases and as those harmonics usually have a very small amplitude compared with the fundamental, a very little error in the oscillograph makes a very large percentage error in the amplitude of the harmonic obtained from it. That method, then, is a very roundabout one, and the authors have worked out a method which really gives what is required by a direct reading, however laborious and complicated the preliminary arrangements may be. The method demonstrated by the authors marks a very great advance on anything that has been done before, and I sincerely hope that they will develop this method to a stage at which it can be handed over to an electrical engineer who is not an expert and enable him to analyse a wave-form with tolerable certainty that the results which he is getting are correct. The wave shown on the screen and analysed by the authors is one in which the harmonics are very pronounced. The practical problem with which the electrical engineer is more often faced is the finding of the relative amplitudes of harmonics which are very small compared with the fundamental. The problem is not merely an academic one; although alternator builders have made great improvements in the wave-form of their alternators, the necessity of eliminating harmonics has also increased on account of the greater use of high-tension distributing overhead wires and the great spread of telephone and telegraph wires. As we all know, one of the principal reasons for eliminating harmonics from wave-forms is to prevent interference with telephone wires running parallel with power conductors, and high harmonics of relatively small amplitude compared with the fundamental are likely to be the chief offenders in this respect.

Mr. B. Hague: The use of a triode-valve generator to produce a standard wave-form rich in harmonics is finding applications in many branches of electrical measurement. It is of interest to note that the principle of the multi-vibrator wave-meter is very similar to that of the device used by the authors; in this instrument a valve generator is used to produce a wave-form containing strong harmonics, the prime frequency of the generator being controlled by a carefully standardized, electrically maintained tuning-fork. The desired harmonic can then be picked out by means of a suitable circuit tuned to resonance with it, in much the same way as that employed by the authors in their analyser. Although the paper is almost exclusively confined to the determination of the amplitudes of the harmonics, I can imagine problems in which a knowledge of the phases of the harmonics might also be required. I should be glad if the authors would say whether their method will easily give these quantities and enable the harmonics to be completely determined.

Dr. G. E. Allan: I think it fitting that this paper should have been read in Glasgow, since it was in Glasgow that the first practical application of harmonic analysis was made: I refer to the Kelvin tidal analyser, and it is a point of interest that a short time ago the Kelvin tidal gauge which recorded the tidal wave-forms was presented to the University by the Clyde Trust. I suppose that Descoudres' method was the first successful application of the dynamometer method. I should like some information in that respect, and for comparison I would point out that the Kelvin instrument was built to deal with four components; Descoudres was able to deal with nine, and we now see that with the new method it is possible to deal with 23 or more components. It seems to me that the authors have materialized Fourier's mathematical process of singling out the different components of a complex wave.

Dr. S. Parker Smith: Is it possible to measure harmonics which are so small as to be invisible in an oscillogram? I have in mind a case where a three-phase line, when the neutral was earthed, interfered seriously with a neighbouring communication circuit. The oscillogram showed strong 17th and 19th harmonics only, but no trouble was experienced when the star point was isolated. The trouble was traced to small 15th and 21st harmonics. Would the authors' device

* Paper by Messrs. J. D. Cockcroft, R. T. Coe, J. A. Tyacke and Miles Walker (see page 69).

† Before the discussion the authors gave a demonstration of the neon-lamp method of analysis by analysing a rectangular wave-form of current up to the 13th harmonic. This latter current, which was passed through the moving coil of the dynamometer, was obtained from the a.c. supply by a special arrangement of three-electrode valves. The analysing current was kept constant so that the audience could read off directly, from a 20-ft. scale, the percentage value of each harmonic present.

enable us to determine the magnitude of such harmonics ?

Dr. M. G. Say : I do not think it is generally realized that this paper is the result of three—possibly four—years of strenuous post-graduate research. That part dealing with the magnitude of the errors to be expected well deserves the attention of other authors in similar circumstances. To my mind, the form of the paper is the best that could be presented, and should certainly provide an example of what Institution papers should be. There appear to be some minor errors in Table I. Referring to the foot of page 74, it would appear that λ_{nx} is given in Equation (4*b*) as $(\omega L/r)[(x^2 - n^2)/n]$. Now $L/r = 1/15$ and $\omega = 314$, so that $\omega L/r = 21$ approximately. Inserting this value for $n = 1$ and $x = 3$ (in the first line of the table) the result is $8 \times 21 = 168$, whereas the table gives 128. The same appears to hold for the other lines of the table. However, if my figures are correct, matters are rather improved than otherwise. It is stated on page 78, with reference to the phase-swinging of the commutator-driving gear, that "it would no doubt be possible to reduce this source of trouble very considerably by using a properly designed motor." Suppose that the alternator under test had a cyclic speed variation represented, say, by a sine wave superimposed on its steady mean speed. Then the commutator and its driving motor would have a cyclic variation representable by a sine wave displaced in phase by a half-period of the frequency of the speed variation. The commutator would never be in true synchronism with the supply, and damping would only reduce the amplitude of the variation and not its phase. A steady reading could not therefore be obtained, and the oscillation might be serious when measuring high orders of harmonics. Perhaps, however, I have overestimated the severity of this trouble. If I read Fig. 16 correctly, it would appear that it is impossible, with the neon-lamp method, to measure the amplitude of the fundamental of the wave-form under test with an accuracy comparable with that to which, say, the 9th harmonic might be obtained. Surely the fundamental is the most important of the harmonics. With this method also the volt-ampere consumption of the saturated transformer circuit is somewhat high: it is given as 10 amperes at 200 volts, or 2 kVA. Does this have any distorting effect on the true wave-form of small apparatus under test ? A very interesting form of harmonic analyser has recently been constructed in America.* Here the supply to be analysed is fed into an input network, paralleled with which is an oscillatory circuit whose natural frequency may be altered continuously in a definite manner by pneumatic power. Thus the analysed wave-form has, as it were, withdrawn out of it, in succession, all its harmonics from the fundamental upwards. Probably by some form of reflecting dynamometer the deflections are indicated on a specially scaled photographic plate, which is moved across the field of the dynamometer beam, again by pneumatic means. In this way the developed negative shows a record composed of a series of troughs and sharp peaks traced on a graph marked directly in percentages and in cycles per second. Any harmonic (indicated by a peak) can be picked out by reference to the base line of frequency. The whole process is said to occupy about 5 minutes and is entirely automatic, and the calibration is approximately constant for all frequencies within a wide range. The accuracy of the instrument is not comparable with that of the present one, but its ease of manipulation offers some advantages. Have the authors something in view on these or other lines which would add to the already considerable value of their analyser ?

* *Journal of the American Institute of Electrical Engineers*, 1924, vol. 43, p. 798; also *Electrician*, 1924, vol. 93, p. 552.

Messrs. J. D. Cockcroft, R. T. Coe, J. A. Tyacke and **Miles Walker** (*in reply*) : In reply to Prof. Howe, it should be pointed out that the demonstration of the apparatus before the audiences in London and the Local Centres was greatly complicated by the fact that, in order to enable the audience to read off the value of the harmonics of a square wave without any calculation, all the harmonics had to be projected on the screen to the same scale. In addition, the fundamental had to be made 100 scale divisions so that the higher harmonics would appear in their proper percentage. The main difficulty arose from the variation of the voltage of the supply mains. This in the ordinary use of the instrument does not cause much trouble because, whatever the voltage happens to be at any instant, it is not difficult to take a snap reading of the wattmeter and the voltmeters and work out the value of the harmonic for the set of readings obtained. It is not necessary to bring back the voltage of supply to some fixed value for each set of readings, as is necessary when all harmonics are to be shown to the same scale. We are making up a portable form of the apparatus which will occupy a space of about 1 foot cube. The process of measuring a harmonic will be nothing more than the plugging in of a suitable capacity, the tuning of a circuit by means of a variometer, and the taking of three simultaneous readings if the conditions are rather unsteady. From these three readings the harmonic is worked out in the manner described in the paper.

Mr. Hague asks whether the phases of the harmonics can be determined. Using the synchronous motor and copper disc commutator as described above, the phase of a harmonic could easily be determined by measuring the shift of the brushes required to give a maximum reading.

Since harmonics of less than 1/1 000th of the amplitude of the fundamental can be detected, it should certainly be possible to determine the approximate amplitude of harmonics of the type referred to by Dr. Smith, which are not visible on the oscillograph but yet produce marked interference.

The authors are indebted to Dr. Say for pointing out the omission in the text preceding Table 1. Table 1 was calculated from Equation (4*a*), using values of R_1 and C actually employed in practice. These values were generally chosen to make $R_1 Cr/L$ of the order of 3. Provided the amplitude of phase swing of the synchronous motor is kept below $\frac{1}{2}°$ the dynamometer reading for the 23rd harmonic will not vary by more than 2 per cent. The power consumption of the saturated transformer can be very much reduced by special design. Dr. Say is quite correct in his contention that it would not be possible to measure the

fundamental of a wave very accurately with the neon-lamp method. It is not intended to do this. The E.M.F. wave induced in the oscillatory circuit is deliberately made to have a small fundamental in order to reduce to a minimum the dynamometer torque and consequent error due to fundamental currents in both coils. This is important owing to the large fundamental in most waves likely to be analysed. Since the harmonics in the pressure-coil voltage are found directly in volts, the best way of determining the value of the fundamental is to find the R.M.S. value of the wave with a good commercial instrument and to correct this if necessary for the effect of such harmonics as may have been found. The method recently developed in America and referred to by Dr. Say is in principle exactly the same as the resonance methods described in Section 2 (1), and is subject to the type of errors there described. Since the eddy-current and dielectric losses cannot be inappreciable at the frequency of the 23rd harmonic, it is difficult to see how the calibration can be constant over the whole range of frequencies required. In fact, no statement is made in the paper as to the possible accuracy of the method described.

ALTERNATORS FOR OPERATION ON A TRANSMISSION LINE.

By N. B. HILL, Student.

[ABSTRACT *of paper read before the* NORTH-WESTERN STUDENTS' SECTION, *6th November, and before the* MERSEY AND NORTH WALES (LIVERPOOL) STUDENTS' SECTION, *13th November*, 1923.]

SUMMARY.

When laying out the design of an alternator that will be used to transmit power over a long transmission line, it is necessary to consider several factors in addition to the specified full-load rating before one can decide on the relative electric and magnetic loadings of the machine, or even the frame size on which it should be built.

In attempting a survey of the problem, the paper was divided into six sections, which may be summarized as follows :—

(1) General discussion of the possible instability of an alternator connected to a transmission line.
(2). Varying-voltage and constant-voltage transmission lines.
(3) A more detailed consideration of the alternator, showing that it is possible to determine directly from its open-circuit and short-circuit characteristics the maximum leading kVA with which it can deal at normal voltage, for complete stability down to zero voltage.
(4) Effect of the exciter on the stability of the generating unit.
(5) Variations in station voltage to be expected when operating the high-tension line switches.
(6) Particulars of an alternator built for a 50-period line demanding a charging current equivalent to 8 100 kVA at 11 000 volts.

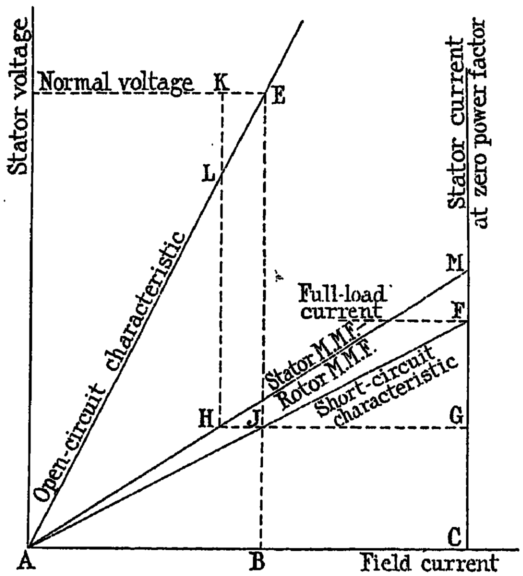
In Section 1 of the original paper, it was pointed out that an alternator connected to a transmission line through transformers becomes a self-exciting unit when the combined "line and transformer characteristic" lies to the right of the "generator characteristic." Without d.c. excitation the voltage of the machine will rise to the point where the characteristic curves intersect.

The "line and transformer characteristic" is the relation between the alternator terminal voltage, and the total leading current taken by the line and transformers. The "generator characteristic" is the relation between the alternator terminal voltage and the leading stator current necessary to maintain that voltage; in other words the saturation curve of the machine when magnetized from the a.c. side. With machines of the size with which we are dealing, it is an advantage if we can make use of the open-circuit and short-circuit characteristics to predict the generator characteristic, as the experimental determination of the former curves does not call for any elaborate tests on the completed machine.

When the machine is excited from the stator, the stator leakage flux provides a portion of the terminal voltage, and the flux crossing the air-gap will be correspondingly less than the flux required to produce the same terminal voltage on open circuit.

Let AE in the figure be the air line of the open-circuit characteristic of the machine, and AF the short-circuit characteristic, E being the point of normal voltage and F the point of full-load current. If we assume zero stator reactance for the moment, the short-circuit curve will represent the relation between stator and rotor M.M.F.'s, and the generator characteristic will be given by a straight line passing through the origin and a point the ordinate of which represents normal voltage and the abscissa a stator current equal to CG. If AB/AC = y, the alternator will evidently be capable of dealing with a maximum charging kVA at

normal voltage of y times its rated full-load kVA. Let us now consider the case where the stator reactance is X per cent, and the open-circuit and short-circuit characteristics are unaltered; we shall assume that the alternator can still deal at normal voltage with a leading current equal to CG. Neglecting the small amount of saturation which is usually present at normal voltage, the portion HJ of the short-circuit excitation maintaining the flux in the machine when the stator current



equals CG, is $XyAB$, and the connection between stator and rotor M.M.F.'s is given by AM. At normal terminal voltage the leading stator current CG now supplies a portion ($KL = XyAD$) of the voltage, and the flux crossing the gap is correspondingly reduced. Since $HJ = XyAB$, and $KL = XyAD$, L must lie on the line AE, and we see that the current CG provides just sufficient M.M.F. to maintain the reduced flux. This means that the generator characteristic is identical with the case of zero stator reactance, and justifies the assumption previously made.

The maximum charging current with which the alternator can deal at normal voltage, for complete stability down to zero voltage, can therefore be obtained directly from the short-circuit characteristic of the machine, by reading from that curve the stator current corresponding to the rotor current needed by the air-gap at normal voltage on open circuit. The maximum charging kVA at normal voltage is thus equal to the normal full-load kVA multiplied by

$$\frac{\text{Excitation required by the air-gap at normal voltage on open-circuit}}{\text{Excitation required to maintain full-load current on short-circuit.}}$$

If the stability is estimated in this way no correction is needed for stator reactance, but it will be realized that this is not equivalent to saying that the stability is independent of the reactance. For example, if by some means we could reduce the reactance of a machine without altering any other of its characteristics, a smaller proportion of the terminal voltage would be provided by a given leading current in the stator, and to maintain the correspondingly increased flux in the machine a larger leading current could be taken from the line—in other words the stability would be increased. This is also evident from the formula given above, since less excitation is needed to maintain full-load current on short-circuit when the stator reactance is reduced without altering any other feature of the machine.

It may be mentioned that the wave-form of the alternator has no effect on the stability. If harmonics are present in the voltage wave these will cause additional currents of a corresponding frequency to flow in the line, but it is only the currents of fundamental frequency that assist in magnetizing the machine. The M.M.F.'s produced by currents of other frequencies move at a high velocity with respect to the field system, and as far as the harmonics are concerned the machine may be considered to be an induction motor on short-circuit.

Since the line capacity is in series with the inductance of the alternator windings, the possibility of voltage resonance, either at fundamental frequency, or at one of the harmonic frequencies, must be considered. From this point of view it is desirable that the wave-form of the alternator voltage should be free from harmonics.

PROCEEDINGS OF THE INSTITUTION.

718th ORDINARY MEETING, 23 OCTOBER, 1924.

(Held in the Institution Lecture Theatre.)

Dr. A. Russell, F.R.S., Past-President, took the chair at 6 p.m.

The minutes of the Annual General Meeting of the 8th May, 1924, were taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

A list of donations to the Benevolent Fund (see vol. 62, pages 558, 651, 728, 816 and 900) was taken as read and the thanks of the meeting were accorded to the donors.

The Chairman announced that the Council had decided to make a donation of 100 guineas to the Cavendish Laboratory, Cambridge, as a token of appreciation of the electrical researches carried out there by Sir Joseph Thomson, Sir Ernest Rutherford and other Cambridge physicists.

The Premiums and Scholarships (see vol. 62, pages 528, 529 and 727) awarded during the session 1923–24 were presented by the Chairman to such of the recipients as were present.

The chair was then vacated by Dr. Russell and taken by **Mr. W. B. Woodhouse** amid applause.

Mr. Ll. B. Atkinson : Once again we meet at the commencement of a new session and a new year's work. Once again we commence those series of meetings of our whole Institution and of our Committees which form so important a part of our work. Again a new and energetic leader takes his place before us, and we are fully confident that he will bring to us, as others before him have done, new ideas and new ideals to which we shall give our heartiest support. But once again also we part with a leader, our President of last session. We consign him delicately to the limbo of past-presidents, to that group of (as it has been stated to me) extinct volcanoes, of which there are fortunately a good many still in existence. Before we do so, however, we want to bid him a grateful farewell—not a farewell in the sense that we shall see him no more, but only in his official capacity. In doing so, we express the belief and the hope that we shall long have him with us to assist us in the work of the Institution and to guide and help those who follow him in the chair he has just vacated. A year ago, when Dr. Russell took over the office of President, we all felt that the Institution was once again fortunate in having the right man at the right hour. It has been a very important year for the electrical profession and industry. That great demonstration of British electrical engineering at Wembley, and the World Power Conference associated with it, have brought together many hundreds of engineers and leading electrical men from all the world over; and it was right and proper that at that moment we should have as our President a man who was internationally known and respected as a scientist. Dr. Russell was such a man. We know him and honour him; and we may well take pride in the fact that during the year he was in office others also showed that they endorsed our view of him. It was during his year of office as President that he was elected a Fellow of the Royal Society, and that his own University of Glasgow, which he visited on the occasion of the Kelvin Celebration, conferred upon him the degree of Doctor of Laws. In his year of office he served the Institution well, at the Council Meetings, at our Ordinary Meetings, on all those occasions when he has had to represent the Institution officially, and in the visits which he has paid to, I believe, every one of our Local Centres. I beg to propose: "That the best thanks of the Institution be accorded to Dr. Alexander Russell for the very able manner in which he has fulfilled the office of President during the past year."

Mr. J. S. Highfield : I have very great pleasure in seconding the resolution proposed by Mr. Atkinson. We all know how admirably Dr. Russell has filled the presidential chair; some of us know of the vast amount of work he has done for our Institution. It is not only what is done by our President that alone is important; the manner of the doing is equally important. By his courtesy and geniality Dr. Russell has done much to enhance the popularity of the Institution. In this particular year when so many foreign friends were here whom we had the honour to entertain, Dr. Russell was a host the embodiment of kindly geniality, carrying in his eyes the light of hospitality, that essentially English characteristic. Truly he concentrated for us our desire to entertain our friends to the full, and in so doing coped with, I believe, some 30 different languages. Mr. Atkinson referred to past-presidents as extinct volcanoes. Contrasted with the new President entering with new eagerness on a year's congenial work, this may be true. But if the work that Dr. Russell does in his ordinary vocation is considered, the skilful training of young engineers at Faraday House, an institution universally respected and held in high honour and in which I know he takes the greatest pride; when it is considered that that work started long before he became President, continued during his term of office and still goes vigorously forward, I am sure you will agree that he, for one, is by no means an extinct volcano. May he live long to enjoy the honour and esteem with which we all regard him. I have the greatest pleasure in seconding the resolution.

The resolution was put to the meeting by the President and carried with acclamation.

Dr. A. Russell: I have to thank you most warmly for the kind way in which you have received this resolution, and especially to thank Mr. Atkinson and Mr. Highfield for the many kind things they have said. What has impressed me most during my year of office is the able way in which our Local Centres co-operate with the parent Institution. The organization by which we keep in touch with our members in all parts of the world is most efficient, and for its smooth working we are largely indebted to Mr. Rowell, the Secretary. I shall never forget the kind welcome that I received, as President of the Institution, from the Local Centres, and also their great hospitality. These friendly relations between the Council and the Local Centres augur well for the future. As an Institution we are deeply indebted to many friends for the unstinted hospitality shown last summer to our overseas visitors. These benefactors include His Majesty the King, Cambridge University, Birmingham University, the London, Midland and Scottish Railway, the North-Eastern Railway, the London General Omnibus Company, Lord Ashfield, and many others too numerous to mention. I very much appreciated the invaluable work done in this connection by Sir James Devonshire, and also by our Secretary. In conclusion, I want to thank the Council and all the members for the great kindness and consideration which they have shown me during my year of office. I am looking forward with the greatest confidence to the continued growth of the Institution in knowledge, influence and popularity under the presidency of Mr. Woodhouse.

The President then delivered his Inaugural Address (see page 1).

Mr. C. P. Sparks: The Address to which we have just listened is one of more than ordinary interest. First, it is written by one who has devoted his entire business life to private enterprise, which, in the opinion of many of us, is the mainstay of this country's prosperity. Secondly, our new President is the first who can speak as a manager of a power company. While it has required many years of hard work for the power companies to establish their position, their importance is now recognized, and they have recently been brought to the fore by more than one political party. Thirdly, our new President is the first for many years who specially represents local interests. He has already served as Chairman of the North Midland Centre for two sessions. I have much pleasure in moving: "That the best thanks of the Institution be accorded to Mr. W. B. Woodhouse for his interesting and instructive Presidential Address, and that, with his permission, the Address be printed in the *Journal* of the Institution."

Mr. Roger T. Smith: Among those who listen to Presidential Addresses I think perhaps those who have already occupied the chair have a distinct advantage. Others can think how much better—or how much worse—they would have done it themselves. The past-president knows how much worse, or perhaps how much better, he did it. But I doubt if there is any past-president here to-night—not even myself—who would be sufficiently vain to think that he had produced an Address better than that to which we have just listened. Teachers, because they generally know nothing at first hand of what they teach, can generally make their lectures interesting, although students will bear me out that that is not always the case. It is, however, a much harder task for a man who has spent all his life in doing things to put the results of his experience into an address confined to one hour, and at the same time to make that account of his work as absorbingly interesting as our President has done; and for his doing that and giving us the pleasure of so instructive and important an Address, I have very great pleasure in seconding the resolution.

The resolution was then put to the meeting by Dr. Russell, Past-President, and was carried with acclamation. After the President had briefly replied, the meeting terminated at 7.30 p.m.

40TH MEETING OF THE WIRELESS SECTION, 5 NOVEMBER, 1924.

(Held in the Institution Lecture Theatre.)

Mr. W. B. Woodhouse, President, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 7th May, 1924, were taken as read and were confirmed and signed.

Mr. E. H. Shaughnessy, O.B.E., Chairman of the Wireless Section, then delivered his second Inaugural Address (see page 60).

A vote of thanks to Mr. Shaughnessy for his Address, proposed by the President and seconded by Professor G. W. O. Howe, D.Sc., was carried with acclamation, and the meeting terminated at 7 p.m.

INSTITUTION NOTES.

Faraday Medal.

At the Ordinary Meeting of the Institution held on the 22nd January, the President announced that the Council had made the fourth award of the Faraday Medal to Sir Joseph Thomson, O.M., M.A., F.R.S., an Honorary Member of the Institution and Master of Trinity College, Cambridge.

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 25 December, 1924–25 January, 1925.

	£	s.	d.
"C. A." (London)		10	0
Abraham, F. H. (Bradford)		5	0
Adams, G. H. (Edinburgh)		10	0
Addis, E. (Crewe)		2	6
Addison, J. D. (Inverkeith)		2	6
Aikman, A. N. (Harrow)		15	0
Alabaster, E. O. (London)		5	0*
Alabaster, H. (Eastbourne)	2	2	0*
Aldridge, T. H. U. (Shanghai)	5	0	0*
Alexander, T. R. (Birmingham)		5	0*
Allan, R. H. (Swansea)		5	0
Allen, A. Hinton (London)	1	1	0*
Allen, C. E. (London)		8	6
Allom, G. F. (London)	1	1	0*
Allwood, H. (London)		10	0
Ambrose, G. S. (Rugby)		3	6
Amerasinghe, R. P. (London)		5	0
Anderson, H. M. (Glasgow)		15	0
Andrews, A. E. D. (London)		4	0
Andrews, O. M. (London)	1	1	0
Angold, A. E. (Birmingham)	1	1	0*
Ardis, R. (Holywood, Co. Down)		5	0*
Ariger, J. (London)		5	0
Armstrong, R. B. (London)		2	6
Arnold, A. H. M. (Liverpool)		10	0
Arnold, C. L. (Enfield)	1	1	0*
Arnold, K. N. (Purbrook, Hants)		10	6*
Ashcroft, E. A. (Waye, nr. Ashburton)	2	2	0
Ashmore, J. (Birmingham)		10	6*
Aston, C. J. (London)	1	0	0
Atkins, R. E. (North Walsham)		2	6*
Aust, O. L. G. (London)		5	0
Austin, H. S. E. (Norwich)	1	1	0*
Bache, W. J. (Cheltenham)		10	6*
Bagshawe, A. S. (Manchester)		10	0
Bailey, A. R. E. (London)		6	0
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Womack, H. A. (Wokingham)		5	0
Wood, A. R. (Ilford)	1	0	0
Wood, G. W. (London)		3	6
Wood, K. L. (Thornton Heath)		5	0*
Wood, W. K. (Birkenhead)		5	0
Woodbine, G. P. (Ipswich)		2	6
Woodford, C. G. A. (Gosport)		3	6
Woodhouse, W. B. (Leeds)	1	1	0*
	10	10	0
Woods, R. C. (Beeston, Notts)		5	0
Woodward, E. E. M. (Croydon)		5	0
Woodward, J. H. (London)	1	0	0*
Woolley, T. G. (Brooklands)	1	0	0*
Woolliscroft, J. H. (West Kirby)		10	0*
Wordingham, C. H. (London)	1	1	0*
Wright, H. G. (Saltburn-by-the-Sea)		10	0*
Yates, J. H., jun. (Bombay)	1	8	6*
Yerbury, H. E. (Sheffield)		10	6*
Young, H. W. (London)	1	1	0*
Young, J. J. (Southport)		4	0
Young, W. (London)		10	6

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SPEEDING UP THE TELEGRAPHS: A FORECAST OF THE NEW TELEGRAPHY.

By DONALD MURRAY, M.A., Member.

(*Paper first received* 15*th September, and in final form* 29*th October; read before* THE INSTITUTION 18*th December*, 1924.)

SUMMARY.

This paper, which is mainly a forecast of the probable form that the telegraph service will take in the course of the next 25 years—a form that is described as the "new telegraphy"—refers to the world-wide complaints about the unsatisfactory condition of the telegraph service and the need for improving it and speeding it up until it takes its proper place alongside the telephone.

It is agreed that these complaints are well founded, and the telegraph service is described as being dear, slow and inaccessible. Speeding up the telegraphs and bringing them into closer touch with the industrial and financial life of the world is put forward as a necessity of the future. We must type as well as talk. We must "teletype" as well as "teletalk."

It is pointed out that the telegraph has many important advantages over the telephone, especially for communicating over distances of more than 50 miles, and the present ailment of the telegraph is diagnosed as excessive circuit facilities and defective terminal facilities. That is to say, there are more circuits than are required for the traffic at present available, and not sufficient telegraph machinery, and the telegraph equipment is not arranged, like the telephone, so as to be linked up closely with the business life of the community. The telegraph is not, but should be, at every business-man's elbow, like the telephone.

The remedy is the creation of printing telegraph or, more briefly, teletype exchanges, giving telegraph facilities similar to the telephone facilities we now enjoy. This will evidently be the result of certain developments now taking place in America, where both the Western Union and the Bell Telephone Companies are about to offer telegraph typewriter service to business men, that is to say to subscribers. If this proves commercially profitable, it will inevitably lead to the establishment of teletype exchanges in all the American cities, and they will be linked up by trunk or long-distance telegraph lines. This will put business men all over the United States directly in touch with each other by printing telegraphy. In this way the new telegraphy will be born.

The paper foretells that, in the course of years, this new development will have a revolutionary effect on telegraph offices, which will become automatic switching exchanges, very like an automatic telephone exchange; and the telegraph operators, like the telephone girls, are doomed to disappear, and their places will be taken by a few telegraph engineers and mechanics wandering about in the deserted telegraph operating-rooms, looking after the telegraph switching apparatus.

Examples are given of the advantages that this new telegraphy will confer on the business community.

The machine that has made this new telegraphy possible is the start-stop telegraph printer—provided with a typewriter keyboard and requiring only momentary synchronism. It can therefore be readily switched from one circuit to another. It can work at from 40 to 80 words a minute over any distance from 100 feet to 5 000 miles, and any girl typist can use it. This is the business-man's printing telegraph—the Ford car of telegraphy.

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Part 1.

THE WORLD'S UNSATISFACTORY TELEGRAPH SERVICE.

(1) *The modern demand for speed, and why.*—A paragraph in the newspapers, entitled "Speeding up the Telegraphs," has supplied the title and inspiration for this paper. The paragraph, which has already been widely quoted and commented upon, appeared in the following form in the London *Daily News* of the 26th February, 1924:—

"SPEEDING UP THE TELEGRAPHS.—RIVALRY OF WIRELESS AND AIR MAILS.

"PARIS, Monday.

"It is announced here that the International Telegraph Union at Berne is proposing a world inquiry into the growing neglect of the telegraph in internal and international communications.

"In some countries, such as the United States and Scandinavia, the telegraph now contributes hardly more than 1 per cent of the total number of electric communications, and in France, where lack of enterprise still leaves over 40 per cent of the 36 000 communes unserved by the telephone, the proportion is only about 10 per cent.

"The air-mail is mentioned as becoming a powerful rival to the telegraph wire. A letter posted in Paris at 7.50 p.m. is now delivered at Casablanca, in Morocco, on the following morning but one, which is not always, but is sometimes, as rapid as the telegraph, and has other advantages.

"In a single month last year 200 000 communications were sent by this air route. The use of wireless telegraphy is growing very rapidly. The great station near Bordeaux sends messages as far as Saigon. Saint Assise serves America, and Lyons, Moscow and Central Europe.

"It is suggested here that if the plant and cables of the old system representing hundreds of millions are not gradually to be scrapped, tariffs will have to be reduced, and the service everywhere speeded up. In France it still often takes five hours to telegraph between Paris and Nice, and this is only an instance of the wide margin left for reform."

The same paper published another significant paragraph on the 18th June, 1924, as follows:—

"TELEPHONING EXPRESS.—QUICKER METHOD OF TRANSMITTING PHONOGRAMS.

"The telephoning of express messages is to be expedited.

"Hitherto a telephone subscriber has telephoned his message to the nearest exchange, whence it has been sent to the next exchange, and so on, necessitating its being re-written perhaps three or four times.

"Under the new system a subscriber is to be plugged through to the nearest central transmitting office. He will be charged only the local fee. A subscriber, for example, who wishes to dictate an express message from Stockport will be put through to Manchester, and one who speaks from (say) Norwood will be put straight through to the Central Telegraph Office, St. Martin's-le-Grand.

"The new scheme is criticized by the Union of Post Office Workers. Mr. Fred Riley, the assistant secretary, said yesterday:

"'The union claims that phonogram work is strictly telegraph work, requiring a full knowledge of telegraphic rules and regulations.

"'In the transfer of work from telegraphists to telephonists the Post Office is guilty of down grading of work contrary to the trade union practice. The union agrees to such transfer only on the condition that telegraph rates are paid.'

"Mr. Riley added that errors in telegraphy were negligible compared with those in telephony. He said the scheme appeared to be a great menace to the staff, and had no advantages for the public."

As these two paragraphs deal with a subject of the greatest importance to the industrial and business world, namely, quick and cheap intercommunication, it seems to be desirable that a clear, hill-top view of the facts and probable and possible developments of telegraphy, as they appear to one who has devoted many years to the subject, should be put on record in circumstances which may lead to wide public discussion. By such discussion the business world will become conscious of the possibilities, and a very desirable stimulus will be given to the growth of the great telegraphic facilities that will be available to us in the course of the next 25 years. I have therefore avoided technicalities, and comcmuniation engineers will find nothing new in this paper, except the unusually extensive landscape.

If we had no telephones, the world would be very proud of its marvellous telegraph service; but the colossal growth of the telephones, and the wonderfully quick and cheap service that they render, have made people dissatisfied with the results at present obtained from the telegraphs.

There have been articles innumerable in the technical and lay Press about the unsatisfactory condition of the telegraph service and the need for cheapening and speeding up the telegraphs to save them from extinction, and all sorts of weird remedies have been proposed. We have been told that the world's telegraphs are in the melting-pot, and that they are liable to be swept away by the telephone and wireless and by the air-mails, and nobody seems to know what to do to remedy this state of affairs. The ideologues and word-merchants suggest that the telegraphs need to be "reorganized," and practical telegraph men recommend "advertising the telegraphs" and "cultivating the telegraph habit." Advertising is good as far as it goes, and the Western Union Telegraph Company finds that this policy pays, and a really remarkable telegraph advertising campaign is carried on in America.

The company has been good enough to send me a collection of its advertising leaflets. These are amazingly clever, and cover all phases of life from the use of telegrams to collect overdue accounts, to sample telegrams to radio artists with the advice "Applaud by Telegraph." Amongst scores of others, there is a card giving the average cost of letters at 52 cents and telegrams at 60 cents. In Great Britain the corresponding cost of an average letter is probably about 1s. and a telegram about 1s. 3d. The argument is that the saving of time at the cost of a few extra cents is extremely profitable. Through all the advertisements runs the refrain: "Don't write—Telegraph!"

Note these last words attacking the mail-bags.

Practical telegraph men realize that telegraph traffic is not likely to grow faster than the slow annual increment due to increase of population, if the present lines of development are adhered to, and they know that there are only two other directions from which increased traffic can be expected. The telegraphs have suffered from the pressure of the telephones on one side and the Post Office on the other, and the obvious remedy is for the telegraph men to attack the telephones and make war on the mail-bags. Hence the advice in the advertisement, "Don't write—Telegraph." There are also night-letter telegrams and various other devices to divert correspondence to the telegraph wires, especially during the ebb-tide when the volume of telegraphic traffic is low.

Clearly this advertising shows that the Western Union telegraph plant is not being used up to its capacity; and that is the position with all telegraph administrations. There is a shortage of telegrams and there is no shortage of telephone messages. Unfortunately it is not much use to advertise the telegraph service while it is dear, slow and inaccessible. When the telegraphs become as cheap, quick and accessible as

the telephones, the telegraphs will not have so much need to advertise.

The chief complaint is about the slowness of the telegraph service, and the complaint is world-wide. For instance, a paragraph in the *Telegraph and Telephone Journal* for June 1924 says:—

"The annual report of the P.M.G. of Australia shows a loss on the telegraph branch of some £78 000 on the year 1922–23. Out there, as here, the speedier delivery of telegrams is a problem not yet solved. It is, however, noted that a distinct promise of an acceleration in that direction has been made."

This demand for greater speed has a deep economic significance, and it may be pointed out, in passing, that the idea of doing things quickly is modern, and it exists only in highly industrialized communities. Some years before the war when I was in Moscow, I was told that "Time is not money in Russia." I was also told that "The Lord God has plenty of time." However, the Russians are adopting modern habits, and all over the world "mañana" is giving way to "pronto."

The explanation of this modern haste lies in the fact that a profit of a shilling an hour is better than a profit of a shilling a day. In other words, the faster one does business the more business one will be able to do and the greater will be one's annual dividend. Every business man knows that, and every business man knows how profitable it is to use the telegraph and telephone. The telephone saves a colossal amount of time, and is one of the main factors in the vast production of modern wealth. The telegraph, the senior service, helps, but not to anything like the extent that it ought to do.

Examples of this speeding up of business may be found throughout every community, and an amusing instance is the speeding up of moving pictures so as to get more programmes through and to get more audiences squeezed into one day. This gives a bigger turn-over in audiences and a bigger profit on the day.

In the language of political economy an essential part of the process of division of labour is exchange of the goods produced, and anything that increases the velocity of that exchange facilitates the division of labour which is one of the two great factors in the production of our modern wealth.

In this speeding up of the turn-over, the telephone and telegraph play a very large part, but the telegraph, for various reasons, has lagged behind. Recent developments, however, with which this paper deals, indicate a great extension of the telegraph service. The business man wants to speed up business, and for that purpose he needs a vastly improved telegraph service, and he is going to get it. He will have to pay for it; but the profit is so great that he will pay gladly when he gets accustomed to the price. By business men I mean not only individuals but organizations, merchants, banks, stockbrokers, factories, railways, farmers—in fact the whole financial and industrial community.

(2) *Telephone versus telegraph.*—In order to get an idea of the possibilities of telegraphy, it has to be remembered that there are only two practicable methods of communication—by the ear, and by the eye. We can talk and we can write; we can telephone and we can telegraph. At present the telephone has no effective rival, it has interwoven itself into the industrial life of the world to an extraordinary degree, and to a substantial extent it is doing work that the telegraph could do better, especially over considerable distances; but for a variety of reasons the telegraph has not been able to stand up against the competition of the telephone, and the result is that the telegraph has been cramped and stunted between the competition of the telephone service and the postal service.

This stunted growth of the telegraph is economically unsound. It is not good for the community, and it is also certainly not permanent. It has been due essentially to the imperfect development of the telegraph plant. It is true that the telephone also is only now reaching the machine stage; but the telephone has always had the great advantage that the transmitting and receiving mechanisms, the human tongue and the human ear, cost nothing, are ready made, and are highly perfected and capable of any speed up to about 150 words a minute. All the telephone engineer had to do was to provide wires and suitable switching arrangements and extremely simple transformation devices to catch and reproduce the human voice. The telegraph engineers, on the other hand, were heavily handicapped by the burden of having to make satisfactory machinery that would typewrite at a distance. This proved to be a very difficult task, and although printing telegraphs have been in existence for 50 years, the business-man's printing-telegraph has only been perfected during the last few years. The reasons will be given later. This is the one and only important reason for the backward condition of the telegraph compared with the telephone. We realize this fact at once when we consider that if we could all speak the Morse Code language the telegraph would not be the Cinderella of communication. It is only now that this handicap is beginning to be removed, and speeding up the telegraphs, or, more strictly, speeding up the transit of telegrams, has begun. This perfecting of the telegraph machinery will be dealt with presently.

It is, of course, hopelessly idealistic to suppose that, for moderate distances, the telegraph can ever be as quick and as intimately connected with the life of the community as the telephone; but we are safe in assuming that in 15 or 20 years business men will have at their disposal a telegraph service, by wire and wireless, far quicker and more accessible than at present, and progressively cheaper than the telephone for distances exceeding, say, 50 miles. If business men could telegraph over distances exceeding 50 miles more easily and quickly and cheaply than they can telephone (and that will be the case by and by) what would be the result? Clearly the new facilities would create much new traffic; but, in addition, many messages now going by telephone would go by telegraph, and also a great many letters that now go by mail would go by wire. The telephone has great advantages over the telegraph, but a perfected telegraph network would have other great compensating advantages over the telephone. We must type as well as talk; we must teletype as well as teletalk. A telephone message is a voice, and nothing more—a sound leaving no record. Nothing is more evanescent. There are sound-recording machines, but the sounds are still

sounds, and there is no conceivable mechanism, outside of the human brain, that will translate a sound-message into a sight-message. It is sight-records and not sound-records that we need for business purposes, because they occupy so little space compared with any sound-record and are so much cheaper. They can also be glanced over so quickly and read at the rate of 300 words a minute. Business demands speed, and we must type and teletype when records are needed. Civilization began when we started to write, and modern civilization began when we started to type. Now we are starting to type by telegraph on a large scale by modern mechanisms.

(3) *Weaknesses of the telephone.*—Not only is a telephone message merely a passing sound, but also in order to gain its undoubted advantages it has to be exceedingly wasteful of signalling material. This is readily seen when we examine the vibrations or signals that have to be transmitted over *two* telephone wires for a single word, say "Paris," compared with the vibrations or signals required to transmit over *one* telegraph wire the same word in the five-unit alphabet.

In Fig. 1, A is an oscillograph record of the electric oscillations in a telephone circuit when the word "Paris" is spoken rapidly into a telephone receiver. I am indebted to the Post Office Research Station at Dollis Hill for this extremely instructive oscillograph.

B (Fig. 1) is a timing record with a frequency of 1 000 cycles or vibrations per second. On B therefore 100 waves mark off $\frac{1}{10}$ second, and it will be seen that the word "Paris" spoken rapidly into the telephone occupied about $\frac{1}{3}$ second, or 1/18th of a second per letter. (Five letters and the space after the word, or, in all, six letters, are taken as the standard word.) Dividing 60 seconds by 1/18 we get 1 080 letters or 180 words a minute. The number of waves or cycles required to transmit the word "Paris" telephonically was 365.

Immediately below, in C (Fig. 1), there has been marked off the number of cycles in B required to transmit the word "Paris" in a telegraph wire by the five-unit alphabet. As start-stop printers use what is really a seven-unit alphabet, we multiply the six letters of the standard word by seven, thus getting 42 units, or 21 waves required to transmit the word "Paris" telegraphically by a start-stop printer, compared with 365 waves required for the telephonic transmission of the same word. It is to be noted that 365 is an average figure, including the low as well as the high frequencies. For a real comparison with the telegraph we have to take the highest frequency that must be used to transmit clear speech, and not the average. If we take this average of 365 cycles for the five letters of the word "Paris," we get 75 cycles per letter, compared with $3\frac{1}{2}$ cycles for the telegraph, a ratio of 21 to 1 in favour of the telegraph.

In D (Fig. 1), I have given the word "Paris" in the seven-unit alphabet transmitted in the same time as the telephone word. This again illustrates the advantage of the telegraph in the fewness and slowness of its signals compared with the telephone. Obviously this handicap in signalling places the telephone at an extreme disadvantage compared with the telegraph so far as the line is concerned, and the longer the line

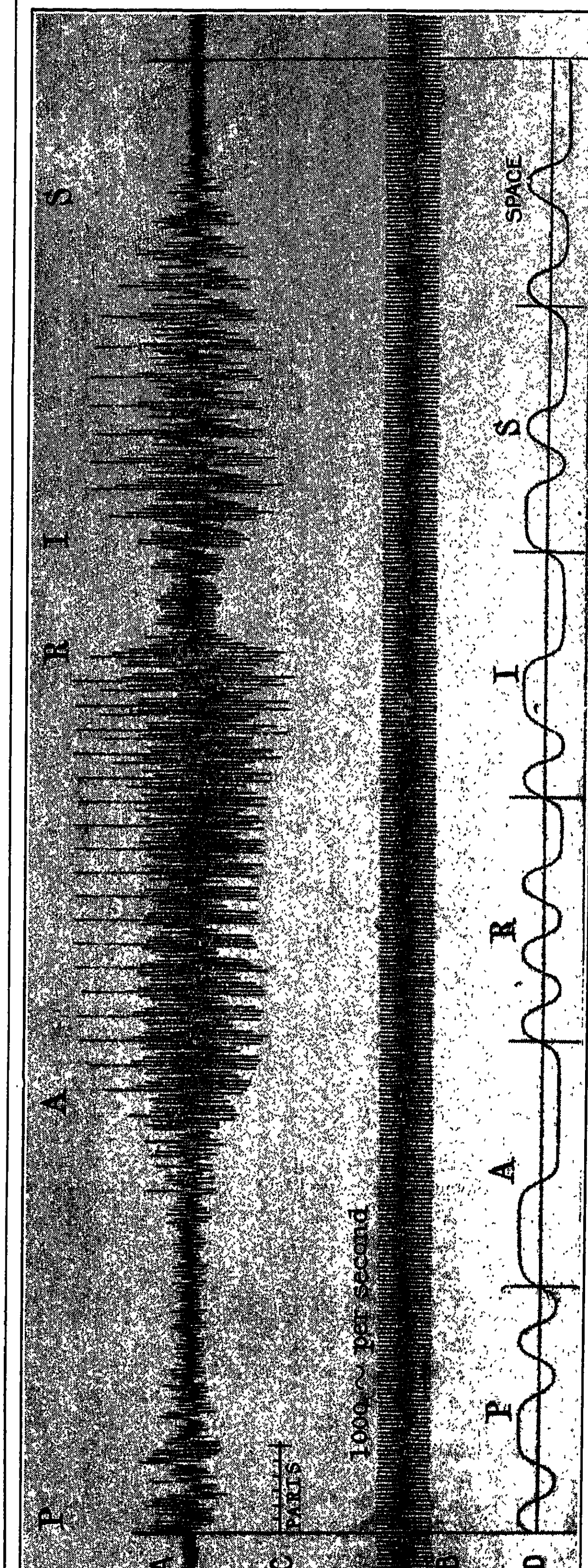


FIG. 1.—Comparative diagram of telephone word and telegraph word "Paris."

Line A.—Oscillograph record of word "Paris" spoken rapidly. Line B.—Time record (1 000 waves per second). Line C.—Telegraph record of word "Paris" in 7-unit start-stop alphabet on same time scale as line A. Line D.—Telegraph record of word "Paris" in 7-unit start-stop alphabet expanded to occupy same time as telephone word "Paris" in line A. This shows the remarkable difference in the number and amplitude of the oscillations in the two cases.

the greater the handicap. Wonderful devices are used by telephone engineers to overcome this drawback; but the same devices can be used in telegraphy, and nothing can remove the handicap.

Another way of comparing the telephone and telegraph, so far as line signals are concerned, is to use the following information, for which I am also indebted to Dollis Hill:—

"The question of the lowest and highest frequency necessary for good speech is very largely dependent upon the quality of speech required. The following figures show the order of values :—

(1) Complete unintelligibility occurs with the elimination of all frequencies above 500 cycles or below 2 000 cycles per second.

(2) Experts can carry on a conversation with all frequencies either above or below 1 000 cycles eliminated, but the quality is poor.

(3) The most important range is from about 600 to 1 200 cycles.

(4) For good quality commercial speech it would probably be advisable to cater for all frequencies between 200 cycles and 2 000 or 2 500 cycles per second, while for perfect reproduction and for music 100 to 5 000 cycles at least are necessary. For the generality of cases 800 is an accepted frequency which can be used to represent speech frequency."

As the weakest link in the chain is the determining factor, we have to take the lowest limit of the highest frequency required for clear speech; that is 2 000 to 2 500 cycles, or, say, 2 400 cycles per second. Multiplying this by 60 gives us 144 000 waves per minute. Dividing this by the $3\frac{1}{2}$ waves per letter used by start-stop printers, we get 41 140 letters, or 6 850 words per minute if we used the same frequency for telegraph work.

The telephone will not give more than 180 words a minute; and actually the average rate is probably not in excess of 120 words a minute. A skilful public speaker does not exceed about 120 words a minute if he is wise, and the rate of the average speaker is about 150 words a minute. It is possible to read silently at the rate of about 300 words a minute. Normal conversation is extremely rapid, and runs up to about 200 words a minute; but such a high speed is impossible on the telephone, because a little more effort is required to speak into the telephone and there is also more effort to hear what is said. Taking the telephone speed, however, at the very favourable figure of 150 words per minute, we find, on dividing 6 850 words per minute by 150, that the telegraph is 45 times more efficient than the telephone so far as the utilization of the line signals is concerned. Even if we come down to what Dollis Hill calls poor-quality speech, namely the 1 000-cycle limit, the telegraph is still 19 times more efficient than the telephone so far as the line is concerned.

This calculation can be put in another form as follows: Taking the standard word as composed of six letters (including the space), 150 words a minute is 15 letters per second. Taking our upper limit of frequency for clear speech over the telephone, namely, 2 400 cycles per second, and dividing by 15, we get 160 cycles per letter for the telephonic transmission of intelligence. In telegraphy the rate per letter, using the five-unit alphabet, is $2\frac{1}{2}$ cycles, or $3\frac{1}{2}$ for start-stop printers. Dividing 160 by $2\frac{1}{2}$ we get a ratio of efficiency of 64 to 1, or with $3\frac{1}{2}$ cycles, 45 to 1, as before.

This takes into account only the handicap of frequency. The telephone, however, also depends largely on varying amplitude of vibration. There are hundreds of different amplitudes with the telephone and only one amplitude with the telegraph. Hence, if we take amplitude as well as frequency into consideration, we shall probably be within the mark in saying that there is a handicap of 100 to 1 on the telephone compared with the telegraph, so far as the line is concerned.

I have gone at length into this comparison, because the whole future of the new telegraphy depends upon it. The figures quoted make it clear why the telegraph can be so much cheaper than the telephone when distance becomes an important factor.

For the information of many non-technical people who, I hope, will read this paper, I may mention that there is a practical limit to the rate of electrical vibration and also to the variation of amplitude that can be transmitted over any given size and length of wire, and the longer the wire the lower the limit. It is this fact that imposes a handicap of 40 or 50 to 1, and even 100 to 1 on the telephone compared with the telegraph.

With the telephone the risk of error is great, because the electric currents representing the voice not only have a very high periodicity but also are extremely feeble. They are likewise very delicate, because varying amplitude is an important factor. To shut out disturbances which would ruin these extremely delicate telephone vibrations, it is necessary to use a loop made up of two costly telephone wires for one message. Also it is only possible to speak on the telephone simplex; that is to say, a man cannot talk and listen to the telephone at the same time. The telegraph can do so. It can work duplex, and the "single-operator duplex" is going to be important by and by. Consequently, the limit of speed on the two costly telephone wires is 150 words a minute, that is to say, 75 words a minute on one wire.

It is true that by various ingenious devices several telephone circuits can be so linked up as to give additional telephone circuits, and there is also the "carrier current" system. But we can apply to telegraphy all these expedients of telephony, including Pupin coils and valves and tone frequencies, the result being many times greater carrying capacity with telegraphy than is now obtained. The position, therefore, is that for working at 150 words a minute by telephone we need two costly telephone wires, that is to say, a telephone loop, or 75 words a minute on one good wire. The telegraph, on the other hand, only requires one wire at about half the cost of the telephone wire, and will give 240 words a minute each way simultaneously, or 480 words a minute in all, on the one cheap wire. This is from 12 to 16 times more than the telephone can do, and the consequence is either a correspondingly greater carrying capacity for the wire, or a correspondingly greater distance covered. It means that for any considerable distance, and particularly for long distances, the telegraph is far cheaper than the telephone. It is for this reason chiefly that the stunted growth of

the telegraph is economically unsound. There is also the great advantage with the telegraph process of being able to store up telegrams in order to send them at opportune times.

There are other serious handicaps to the telephone. For instance, it is impossible to talk in the absence of one of the parties to the conversation, and it is often a waste of time to have to receive a telephone message personally. In this respect telegraph printers offer the notable advantage of recording messages in the absence of the addressee, thus avoiding interruption of work and delay, the messages being stored automatically until an opportune moment arrives. Writing or typing a message saves much time. A business man in the morning finds a pile of letters opened by his secretary ready for him to read and reply to by the aid of his stenographer. In an hour he can dispose of matters by letter that would take him all day, even if possible at all, by telephone.

A letter is a great time-saver. We can dictate a letter when we please and when we have time, and the dictation can be interrupted by more urgent work and no harm is done. We have time to think when dictating a letter. Also the recipient is saved a great deal of time. He can glance through a dozen letters in the time that he would receive one corresponding message by telephone, and he can deal with letters at any time and in any way he pleases. He also has time to think about them and hunt up information. Under suitable conditions many of such letters could be sent by telegraph with great saving of time and without diminishing the foregoing advantages. It would not be practicable to send such letters by telephone. It would be too costly, except over short distances for which the post is better, there would be no typed record, and the possibilities of mistake by telephone are too great for commercial security.

The telephone, in its own way, is also a great time-saver, especially in getting an answer back forthwith; but let me repeat: We must type as well as talk; we must teletype as well as teletalk, and the reasonably perfect telegraph service, as good as the telephone, such as we expect to see in 15 or 20 years, will certainly do a lot of work well, now done by the telephone badly.

(4) *Other competitors of the telegraph.*—In the first paragraph quoted at the beginning of this paper reference was made to the competition that the telegraphs have to suffer from wireless and the air mail. This is a mistake. It is true that wireless offers great possibilities for rapid communication. Wireless, however, considered from the point of view of this paper, has only indirect connection with telephone and telegraph work. It is really a remarkable substitute for telegraph and telephone wires and submarine cables, and it multiplies the facilities for the use of the telegraph and telephone. A telegram is a telegram whether it is sent by wire or wireless, and wireless need not, therefore, be further considered in this paper.

So far as the air-mail service is concerned, it cannot compete with the telegraph except for handling documents. In this particular respect, aeroplanes may help to empty the ordinary mail-bags, but the risk of loss of valuable documents is too great in the case of aeroplanes; and for urgent communications such as are suitable for telegraphy the aeroplane has no chance in competition with the telegraph. Take London and Paris; under the most favourable conditions it takes about 4 hours for a letter posted in London to reach Paris by air mail.

The actual time of transit at the present day is as follows:—

Charing Cross to Croydon Aerodrome, about 40 minutes; Croydon Aerodrome to Paris Aerodrome, about 2½ hours; Paris Aerodrome to Paris, about 30 minutes; Total time of transit, about 3 hours 40 minutes.

This takes no account of the time required to make up the mail in London and to deliver the letter in Paris. Taking the total time at 4 hours, only 20 minutes would be allowed for posting and delivery. The speed of commercial aeroplanes is only about 80 to 90 miles an hour, and even this speed is greatly affected by the wind. If we reckon 100 miles an hour for the aeroplane, it would take more than an hour to post, transport and deliver a letter between London and Birmingham. With the new telegraphy between London and Birmingham, a message would go through from typist to reader in about 2 minutes, and a reply would go back within another 2 minutes if the subject-matter permitted an immediate answer. A properly developed system of telegraphy would deliver a long telegram from a correspondent in London to a correspondent in Paris within 10 minutes. The new telegraphy has nothing to fear from the air mail.

So far as the postal service is concerned, the fundamental advantage is the extremely cheap rate of postage, 1½d. per letter, and the letter may contain several thousand words if closely typed on thin paper. One reason for this cheapness is that the paper and envelope of an ordinary letter are not supplied by the Post Office, and the labour of writing or typing the letter is not done by the Post Office. There is distinct material- and labour-saving in this, or, more strictly, a transfer of labour and cost of material from the Post Office to the individual or firm, just as automatic telephones transfer the labour of making a connection from the telephone girl to the subscriber. It will be seen that the new development of the telegraphs foreshadowed in this paper will effect the same transfer of labour from the telegraph administration to the individual or firm. Another advantage of the postal service is that cheques and other documents that cannot be telegraphed or telephoned can be sent easily and cheaply by post. The great handicap of the mail, and one main reason for its cheapness, is its extreme slowness, at the outside 60 miles an hour on land, and by sea not more than about 25 miles an hour, and even by aeroplane not more than 120 miles an hour. For short distances within city limits this drawback is trifling and, on account of the extreme cheapness of the service, all communications that can stand a few hours' delay will always go by post within city limits. The greater the distance, however, the greater the advantage of the telegraph for messages requiring speedy delivery.

There is appropriate work for each of the three services of communication, the post, the telegraph and the telephone. There are certain things that each

can do better than the other two, and during the next quarter of a century the telegraph will recover ground which, through transient causes, has been lost to the telephone and postal service.

(5) *The defects of the telegraph service.*—The defects of the telegraph service are not appreciable to the average man, and it is not until we begin to consider how the telegraph service might be improved and how inferior it is compared with the telephone, that we realize that it is slow, costly and inaccessible. For moderate distances the telephone is as cheap as the letter post, and we can get through to anyone we want in a minute or two. The telephone is quick, cheap and very accessible. At my desk I am in close, quick and cheap touch with London, thanks to the telephone, and I ought to be in similar touch with the world by telegraph, but I am not. The telegraph does not possess the close linkage enjoyed by the telephone with the business world. It is true that I can telephone a telegram to the Central Telegraph Office, and so speed up the telegram to some extent; but at the Central Telegraph Office my telegram or cablegram has to do a lot of "circulating" before it reaches the point of departure over the telegraph line or the ocean cable, and at the other end it has to do more "circulating" before reaching its destination. The telephone-telegram, or, as the British Post Office calls it, the "phonogram" service is a valuable facility for an occasional telegram or cablegram; but it is a nuisance if one has to send many telegrams, and it is far from accurate, unless the message is repeated and the words spelled out analogically, "T" for Tommy, "H" for Harry, and "E" for Edward. That makes it irritatingly slow when sending many telegrams. The telegraph, with proper machinery, could beat the phonogram with ease when numbers of messages are concerned. Obviously, compared with the telephone, the telegraph is at present very inaccessible, and it is nothing like so quick. It is cheaper for long distances, but dearer for short.

The defects of the telegraph are clearly not due to lack of circuit facilities. There are enough telegraph circuits to carry more than double the present available traffic. There are, indeed, excessive circuit facilities, as will be explained presently. It will be found upon investigation that the shortcomings of the telegraph service are due almost entirely to defective terminal facilities. The patient's condition may be diagnosed as "excessive circuit facilities and defective terminal facilities." Fortunately the prognosis is favourable. The terminal facilities are going to be greatly improved in the course of the next 25 years, and the resulting increase of telegraph traffic will absorb the excess of circuit facilities.

Looking at the telegraph situation to-day, we see good organization and capable management; but we also see excessive development of circuit facilities, due to competition and to international jealousies and to unforeseen technical improvements. Side by side with the complaints about the unsatisfactory condition of the telegraph service, there are many reports in the Press about more telegraph cables to be laid. New and wonderful "permalloy" cables are being made to give 300 words a minute instead of 30 across the Atlantic; the nations are insisting upon having their own cable and wireless services; and investors are beginning to wonder where the traffic is to come from to pay interest on the heavy capital expenditure. Another important element in the creation of excessive circuit facilities is the widespread provision of telephone trunk lines, each composed of two wires; and the ease and cheapness with which telegraph circuits can be created by superposition on these telephone trunk lines adds to the present superfluity of telegraph circuits. Telegraph-circuit facilities are also increasing to an extraordinary extent in consequence of technical developments in radio-telegraphy, which have shed new light on the solution of old telegraph problems, and have shown how to split up one wire into 10 or more channels. There are phantom circuits, superposed circuits, carrier-current circuits or wired-wireless telegraphy giving wonderfully increased carrying capacity; and quite distinct from this are tone-selective methods or harmonic telegraphs, which appear at last to be getting on to a practical basis. Then, in addition, we have wireless telegraphy constantly improving its methods and range and practical carrying capacity. Some time ago that wise old institution, the British Post Office, seeing how matters were developing, altered the wording of its contracts for leasing wires by inserting the words "channel of communication" instead of "wire," so as to reap the benefit of the rental of, say, 10 or more channels into which one wire may now be split up. It is probably not an exaggeration to say that the present telegraph plant of the world, wire and wireless, can handle twice the present volume of traffic; and technical developments, now past the experimental stage, can multiply the present telegram-carrying capacity by 10. In other words, the telegraph circuit facilities of the world are, on the average, at least twice as great as the available traffic, and these facilities, by the expenditure of 15 to 20 millions sterling, can be increased sufficiently to handle from 15 to 20 times the present traffic.

But these wonderful facilities suffer from a grave defect. They do not link up closely with the business man. The telephone does, and the telegraph does not. The telegraph has to get the assistance of the telephone to complete the linkage. That is quite satisfactory for the occasional telegram and for the private and domestic message; but big users of the telegraph require something better. They need a telegraph linkage that will put them directly in touch with their correspondents, just as the telephone does. The really important part of the telegraph traffic is that devoted to business, and this paper is concerned chiefly with business telegraphy.

There is another important point to be borne in mind when considering future telegraph developments, and that is the underground cable. The world cannot afford to have communication between its great cities interrupted by the weather. Within comparatively few years all big cities will be connected by underground cables both for telegraphs and telephones, and this will alter the aspect of circuit facilities. Underground cables give conditions which are so stable and so free

from disturbance when loop circuits are used, that circuit facilities depending on the use of feeble high-frequency vibrations will become much more usable than they are at present. Aerial lines have to be employed as loop circuits like telephone lines to get satisfactory results by these new high-frequency methods, and it is a very interesting question whether such high-frequency aerial-loop circuits can show any commercial advantage over the ordinary multiplex. On underground cables, however, the conditions are very favourable, and attention is being directed to the question of using carrier-current methods, or, more strictly speaking, voice-frequency or tone-selective telegraphy for underground wires. American engineers—including particularly those of the Western Electric Co. and the American Telegraph and Telephone Co.—who have achieved such remarkable results with the carrier-current principle, have also employed these voice-frequency methods; and Siemens and Halske in Germany have worked along similar lines. The latter have issued an interesting pamphlet describing their system of "Tonfrequenzwechselstromtelegraphie." Using only telephone frequencies, fair distances can be spanned without repeaters by such systems, and, by employing the multiplex on each tone-selective circuit, two wires could provide 40 traffic channels. In the case of the Siemens and Halske system, the pressure used on the line is only 1 volt (underground circuits being free from weather and other disturbances), and therefore no trouble is caused in neighbouring telephone loops in the same cable.

Of course the plain multiplex, working duplex, can give 12 channels on a single wire without difficulty, and there is nothing inherently impossible in working the ordinary multiplex up to 12 channels each way simultaneously on one stable circuit such as an underground cable can give, should the improvement of terminal facilities create a demand for increased circuit facilities. Indeed there are grounds for contending that for the wire-splitting required by the new telegraphy, the unaided multiplex is superior to any other method on lines of considerable length.

(6) *They arise from lack of terminal facilities.*—Although telegraph circuit facilities greatly exceed present requirements, there is one respect in which the telegraphs are very deficient, and that is in terminal facilities, or, in other words, in machinery, which in most countries is still old, inefficient, clumsy and stupid. No doubt this will provoke a smile, and people will say that I, as a telegraph machinery merchant, am using the shoemaker's argument that there is nothing like leather. It is true, nevertheless. The terminal facilities are bad and incomplete, and it is because of the defective terminal facilities that the telegraph lags so far behind the telephone. Also, a large portion of telegraph traffic is still handled by the morse key. That is the same thing as using a pen. We have to use a pen to sign letters, and the morse key will always be with us; but letters are typed nowadays, and the typewriter keyboard should be as supreme in telegraphy as it is in business. That condition is coming rapidly. It is in full flood in the United States, and it is to significant developments in the United States that I want to call special attention this evening. The era is beginning when typewriter keyboards in the offices of business men will not merely type letters, but will type and transmit telegrams direct to correspondents in any part of the world. At last the missing link will have been supplied, and the telegraph service will secure the direct connection with business that has been so long the monopoly of the telephone.

In certain cases this is not a new development. For the past 10 years at least, the distribution of news, for instance, has been linked up directly from the news centres to the newspapers, and the news distributing network in English-speaking countries is cheap and quick and highly efficient. Also stock and exchange brokers in big centres like London and New York have not much to complain about, though the telegraph service will be improved, even in their case, by the increasing use of the typewriter keyboard. It is in connection with the banks, the big financial houses, large hotels, big stores, the railways, great industries and manufacturing plants, and, above all, the great farming industry, that a quicker, cheaper and more accessible telegraph service is badly wanted.

It is true that the telegraph has already been brought into offices and factories, but only to a relatively small extent. There are many firms using rented telegraph wires with morse key and sounder and morse operators, especially in the United States. In this country, stockbrokers and other firms use the telegraph to some extent; but they are hampered by the necessity of employing a skilled morse operator at each end of the line, and they cannot ring up anybody by telegraph, as they can by telephone. In other words their telegraph service is poor. It is cribbed, cabined and confined to one correspondent. Even now, stockbrokers, for instance in Glasgow, are each glad to pay nearly £4 000 a year for a private telephone line to London, though the telephone is notoriously bad for transmitting figures. A telegraph wire with the morse key would be cheaper, but it would be too slow. Competition is keen and a delay of 2 or 3 seconds in getting prices from London will result in business going to a competitor. There is also the considerable cost in wages of a morse operator at each end of the line.

Part 2.

The Twin Remedies.

(1) *Start-stop printers.*—The defective terminal facilities are due to a variety of causes; amongst others, to lack of faith and foresight on the part of telegraph administrations, and to a determination to buy cheaply by encouraging competition to such an extent that telegraph manufacturing does not pay. There is a natural tendency on the part of big consumers to encourage competition amongst manufacturers who supply them. The officials in the Reichspostamt in Berlin, long before the war, told me they liked to encourage competition, as they did not want the Reichspostamt to be at the mercy of one firm. This is the old Roman policy of "Divide and Conquer," and certainly printing telegraph inventors and manufacturers are a conquered race of helots who have made no particular profit up to the present out of printing telegraphy, or at least no

profit in proportion to their efforts and to the service they have rendered. This has resulted in telegraph development work being starved and stunted. Also the inventive and development work has been very intricate and deceptive. Arrangements generally recognized as excellent have proved to be hopeless in practice; and other solutions, that looked unpromising, have proved to be good. Lack of capital, lack of experience, lack of knowledge of the best ways, have all put the brake on progress until comparatively recently. Printing telegraphy has been a tropical jungle, with the axe in use all the time, and no compass and no map. It is only within the last 10 years that the multiplex in its modern form, with typewriter keyboards and speeds to correspond, has won acceptance as the best machinery for trunk-line telegraphy; and it is only within the last 2 or 3 years that the second great step, probably the greatest step of all, has been taken in the successful development of start-stop printers. It is only just dawning on the telegraph world what an immensely important thing the start-stop printer really is, and that it is the long-sought missing-link which will complete the telegraph network and give the world a really efficient telegraph service corresponding to the highly satisfactory telephone service to which we have been accustomed for years. It is true that in some countries the telephone service is not efficient; but that is not the fault of the inventors and manufacturers. The equipment is available. In the case of the telegraphs the equipment has not been available until now.

Before dealing more in detail with the start-stop printer special attention must be devoted to the question of using start-stop printers like the teletype, through telephone exchanges or through special teletype exchanges. Telephone experts inform me that there are grave engineering objections to the employment of telegraph machines through a telephone exchange; but these difficulties are not insuperable. During a recent visit to Paris, I was informed that a telephone engineer in the French Administration had devised a very simple instrument which would enable the teletype to be worked through any telephone exchange. I was also informed that a second device for the same purpose had been invented in Paris. I have no details, but I suppose it is done by that modern lamp of Aladdin, the valve, which enables very feeble currents to be used. In France considerable importance appears to be attached by technical men to this possible development of using the teletype in conjunction with the telephone for working through telephone exchanges; but it would appear to be better in all respects to have separate teletype exchanges. (I may explain here that in this paper I am using the word "teletype" more or less as a generic term. What is said, of course, applies equally well to any other printer designed for the conditions of the service.)

Apart from the engineering difficulties, one argument that has been advanced against the use of the teletype or other start-stop printers on telephone lines, is that such an arrangement would load up the telephone wires in a very undesirable manner. Subscribers to the telephone service buy the right to communicate with other subscribers, and if the other subscribers block up their wires with teletype as well as telephone communication, the result will be either that there will have to be special teletype as well as telephone wires, or the engaged signal will be heard much oftener than now and subscribers will not get what they pay for, namely, quick telephone service.

There are two answers to this argument. In the first place, if a subscriber loads his telephone line to such an extent that other subscribers have difficulty in getting through to him, the proper remedy is for him to get another telephone line, and in fairness to other subscribers the telephone authorities quite rightly insist on his doing so. The other answer is that the use of the teletype will not in this generation exceed, say, 5 or 10 per cent of the telephone calls, and the effect of this on the telephone traffic load would be trifling—and it would be much less if the subscribers making much use of the teletype had separate wires.

(2) *The teletype exchange.*—Evidently, however, the separate teletype exchange is the best arrangement; but this does not mean that there will be separate teletype exchange buildings. The telegraph traffic would not warrant such expense, except in a few special cases. By a separate teletype exchange I mean a small separate section in a telephone exchange devoted exclusively to start-stop telegraph circuits. It will be seen that such provision for teletype work will be sufficient if we realize that a total of 50 000 teletype exchange subscribers in London would probably not be reached for many years, though much will depend on the price of the teletypes. If they ever come down to the price of typewriters (and this is a possibility within the next 25 years) the number of teletypes in use would grow immensely, and no business man could afford to be without a telephone, a teletype, a typewriter, and a typist. The problem of the next year or two, however, will be to provide for perhaps 1 000 or 2 000 teletype subscribers. To this number would be added the local post offices and telegraph substations, telegraph offices in big hotels and stores, and also a big central teletype exchange at the Central Telegraph Office in London, for handling all the telegraph traffic reaching that office. Clearly 1 000 or 2 000 teletype subscribers divided over 100 telephone exchanges in London would not cause much inconvenience by the requirement of a special teletype section, and even 50 000 teletype subscribers would only average 500 for each exchange. On the other hand, probably most of the teletype subscribers would be concentrated in the City, and it would be cheaper and quicker to take them direct to the central teletype exchange at the Central Telegraph Office.

The teletype exchange equipment would be substantially the same as for telephones, and, as the maintenance and supervision would be the same and by the same staffs, the cost of a teletype section in a telephone exchange would therefore not be great.

Although there are engineering difficulties in working telegraph apparatus through telephone exchanges, it ought to be practicable for a subscriber having one telephone line and a teletype to ring up the telephone exchange and say "teletypes." He would then be plugged through to the teletype section, and it would

appear to be a simple matter for the teletype section to cut off his telephone loop completely from the telephone exchange and connect it to the teletype section. Wiring alterations would have to be made, but the alteration for each subscriber ought not to be great or costly. The subscriber having got through to the teletype section, a switch in his office would enable him to cut out the telephone and cut in the teletype. He would then teletype to the teletype exchange stating his requirements, and he would be put through in the same way by the aid of the telephone in the case of a local call, or direct to the central teletype exchange for a trunk or long-distance call, and he would then have his message typed direct at its destination. The *sine qua non* for improvement of the telegraph service is close co-operation between the telegraphs and the telephones, and the foregoing teletype call is an illustration.

(3) *Resulting in the new telegraphy.*—The teletype exchange plan, if it succeeds, will in time effect a complete revolution in telegraph methods and organization in head telegraph offices, especially in large cities, which will be provided with automatic telephone exchange equipment for the teletype exchange. The telegraph operator belongs to a doomed profession and he will disappear, for the same reason that the telephone girl is being driven out by the automatic telephone switches. On the other hand, there will be an increase in the number of engineers, and gangs of mechanics will wander about in the otherwise silent and deserted galleries at St. Martin's-le-Grand, and the screwdriver and the soldering iron will take the place of the morse key and sounder. The general public will continue to write out their occasional telegrams and hand them in at the nearest telegraph office. There, calls will be put through to Glasgow or Manchester or elsewhere, and the telegrams will be teletyped direct to their destinations. Every hotel and public place will have a teletype for delivery and reception of telegrams. There will be teletype call-offices or pay-stations at hotels, big stores, underground stations, post offices and other convenient centres, where it will be possible to use the teletype on similar terms to the telephone in similar circumstances, namely, payment of a sum according to time and distance.

The teletype can be left ready for receiving messages all night. Unlike the telephone, the teletype records messages without human assistance, and when the business man comes to his office in the morning he will find telegrams and cablegrams that have arrived during the night or early morning. For example, if we are in a country village in Kent and late at night we receive by telephone an important telegram from McDonald and Co. in Glasgow, we shall telephone our reply as a phonogram to the nearest telegraph office. There a teletype call will be put through to McDonald and Co. in Glasgow and the message will be printed direct on a teletype in their silent and deserted office ready for action when the office opens in the morning. There will be only one transmission and only one typing of our message, and there will be no "circulating" and no telegraph operator and no message-boy in Glasgow. The message will go direct and be recorded without human labour. Kleinschmidt makes a feature of this point in his advertisements of his start-stop printer. It records messages all night in empty offices at railway stations ready for the staff in the morning.

As another example of the new telegraphy, let us consider a large manufacturing plant, say in Newcastle, equipped with start-stop printers, such as teletypes. There would be a private-branch teletype exchange, as well as the usual private-branch telephone exchange. Orders and other departmental communications that have to be typed would go through the private teletype exchange, and any department could at once send a telegram through the private teletype exchange on to the Post Office telegraph wires, let us say, to a firm in Glasgow, the Post Office plugging the department direct through to the Glasgow firm, and the department would get a reply probably at once, or at any rate with only a few minutes' delay. That would be far more convenient and cheaper and quicker and more accurate than the telephone. Similarly, any department of the big manufacturing plant could receive outside telegrams direct, with substantial saving of time. In future days when there will be a dozen of the new permalloy Atlantic cables in use, each working at 300 words a minute in each direction simultaneously, and all fitted with sextuple duplex multiplex, there will be no difficulty in sending a message from any department of the manufacturing plant in Newcastle to San Francisco or other American city, and getting a reply within 10 minutes, subject always to the conditions of daylight between Europe and America. The circuit facilities will be still greater when half a dozen wireless beams work across the Atlantic, each at 300 words a minute.

Another important feature of the new telegraphy will be the assistance it will give to small newspapers which cannot afford to have a private wire of their own. Small country, local suburban and weekly journals would be glad if they could get news on 3-minute teletype calls. It would be cheaper than the telephone, more reliable and much more convenient, as the teletype would print the messages ready for use. In most cases these teletype circuits would be superposed on telephone lines. The teletype exchange is undoubtedly going to have a large effect on the distribution of news.

(4) *Printing telegraphs for farmers.*—Still another example of the new telegraphy must be given because of its great importance, and because it will open up an entirely new field for telegraphy. It may sound ridiculous to people in Great Britain, where the farming industry is so backward and unprofitable, but it is a fact that it is to the farming industry—the greatest and oldest of all industries in all countries—that the start-stop printer will render the most important service. In other lands, and especially in new countries, there is a very large and prosperous farming and plantation, and station- and ranch-owning class, especially in North America; and market prices are just as vital to such farmers as to any stockbroker; and another thing vital to the man who ploughs the land, as well as to the man who ploughs the sea, is the weather. The sailor must rely for his weather reports on his barometer and wireless, but not so the farmer, who can also have his teletype.

In Australia the inch of rain is divided into 100 points, and weather reports are distributed and put up by the

Government on the bulletin board at every country post office or railway station; and the keen interest that the settlers and station-owners take in these weather reports is astonishing. The fact that 3 points of rain have fallen at a township 30 miles away is a matter of intense interest. Rainfall or no rainfall spells wealth or ruin to the farmer and station-owner. In other lands warnings about storms and blizzards are not less important. Prices of sheep and cattle, pigs, wool, hides, wheat, butter, coffee, tea, rubber, and other farm, station, plantation and ranch produce, not only at the nearest local market, but in the big markets of the country, and also the world prices, bring wealth or poverty to the man on the land. Next to the stock market and produce brokers, there is no other man in the world so interested in prices as the farmer, and the farmer's concern about the weather is proverbial. The latest market and weather reports are so valuable to him that he will pay gladly for them, just as the stock-broker pays willingly for his ticker service. Hitherto the farmer has never had an opportunity to pay for it. He will also appreciate getting a prompt service giving all the important news of the world.

The start-stop printer, for the first time, fills the requirements of the farmer for a stock-ticker service and it is far and away superior to any stock-ticker. The speed is greater, 40 to 80 words a minute; it will work over any distance, 5 000 miles if necessary; it can be superposed on the farmer's telephone circuit; it can be used on a farmer's party line jointly with other farmers; and it has a keyboard on which the farmer can send out messages as well as receive them. After reading the market prices he can give immediate orders on the teletype to buy or sell. By means of the teletype keyboard, he can communicate with his neighbours along the top wire of his fences. (In Australia, on the great sheep stations, the head station is always in communication with the outstations by telephone along the fencing wire.) Of course, start-stop printers are not suitable for the remote districts; they need an occasional inspection and a drop of oil, and also electric power to drive them. That is a fairly simple matter in the settled districts of the world, where also the distances are not so great as to render the cost of the telegraph or telephone line prohibitive; but even in newly opened-up country with a sparse population there is always the local post and telegraph office (often the general store and centre of gossip for the whole countryside), and a teletype at such a centre would pour out invaluable news of the world, including prices and weather reports, printed on tape ready for the bulletin board, giving a flood of news that could not be received in any other way. In such a case the electric power problem would be difficult, but not insoluble.

Taking more particularly the United States, because of the enormous number of very prosperous farmers in that country it is obvious that farm news-distributing organizations will spring up all over the country for the supply of market and weather reports and other news of interest to farmers, and the farmers will have the opportunity of talking back on the keyboard of the teletype. It may be said that it will be cheaper for the farmers to listen to market and weather reports broadcast by wireless; but a little consideration will show how hopeless that is. To get wireless reports the farmer or some member of his household would have to be in attendance at fixed hours to write down the wireless news. The idea of a farmer or his wife or family trying to note down market prices rattled off quickly by wireless is absurd. Even if this were possible, there are the inaccuracy of wireless, interference troubles and atmospherics, and there is no way of answering back. The only practical plan is a tape-printing teletype recording any news accurately in plain type without human labour, and on duty at all hours. The farmer and his household can read the news and market reports at any time at leisure and he can also get a service of general news. The market reports can be far fuller, as well as far more accurate, than would be possible by any wireless distribution, and far quicker than through any newspaper. The teletype will bring the farmer right into the Chicago Wheat Pit and other market centres. He will know and compare the latest prices straight from the sales of his local market town and also from the big centres of the world.

The prosperous farmer in America and many other countries has his telephone and his motor-car as a matter of course, and it is certain that as soon as the opportunity presents itself and he gets accustomed to the idea, he will add the teletype to his telephone and his wireless set, and in time he will value his teletype above all his earthly treasures. When the farmers of the world adopt the teletype superposed on their telephone circuits, we shall have real telegraphy—a vast printing-telegraph network of wire nerves linking up all industries and all countries.

(5) *Starting the new telegraphy.*—That this idea of teletype exchanges on the lines of telephone exchanges is not a mere speculation is shown by very interesting developments in the United States. Realizing the importance of the machines, the Western Union Telegraph Co. has been giving careful attention to the development of start-stop printers for some years, and this class of machine appears at last to have reached a sufficiently reliable and permanent form to justify the Western Union in offering to furnish its patrons with printing-telegraph service. That will, of course, include circuits and printers connecting patrons to the head telegraph office of the Western Union in each city. The Western Union will also no doubt supply what is known as point-to-point service—that is to say, will connect any two points desired by telegraph lines and start-stop printers. In other words the Western Union is arranging to sell telegraph typewriter service to business men and firms—that is to say, to subscribers. Assuming that the scheme proves popular and commercially profitable, then the Western Union will have hundreds of subscribers in New York alone, to say nothing of other cities. Inevitably the company will have to supply intercommunication between these subscribers. The object of the subscribers or business men buying printing-telegraph service in New York will be to send and receive telegrams quickly, and they will want to do that between each other and also over long-distance telegraph wires with subscribers in other cities. It is clear that if the Western Union can secure a considerable number

of telegraph typewriter subscribers in the leading cities of the United States, then the printing-telegraph exchange and the new telegraphy will have been successfully inaugurated. The Western Union being a very big, old telegraph company with great resources and 50 years of accumulated experience of printing-telegraphy in all its forms, and operating in a great and highly industrialized community, is specially qualified for making a success of the new telegraphy, if that is commercially possible under present conditions.

Another element that makes for progress is competition, and the Bell Telephone Co. is starting to sell telegraph typewriter service to business men in Chicago on similar lines to the Western Union. Chicago, being a great business centre in the heart of the United States, is very favourably situated for the growth of the new telegraphy. I have a copy of a handsome booklet, artistically illustrated and persuasively written, which the Bell Telephone Co. is issuing in Chicago, with the idea of inducing business men to buy printing-telegraph service. It does not propose to establish a printing-telegraph exchange, but simply to supply wires and printing-telegraph apparatus to enable firms to link up their various branches and offices by a private printing-telegraph wire system. Although there is no mention in the pamphlet of a printing-telegraph exchange, a moment's reflection will show that, just as in the case of the Western Union, the existence of a number of private printing-telegraph networks each linking up the various branches of one firm's activities in Chicago would soon lead to a demand for intercommunication facilities, and that would result in a printing-telegraph exchange. If the Bell Telephone Co. finds that selling printing-telegraph service to business men and firms in Chicago is profitable, then it will lead inevitably to the teletype exchange and so on step by step to the new telegraphy. The pamphlet is called: "The Doorway of Opportunity"—"Telephone Typewriter Service"—"It Typewrites by Wire."

(6) *"The Doorway of Opportunity."*—The booklet describes some of the attractive features of the telephone typewriter service, and as the subject is of such great importance I quote some of the paragraphs as follows:—

"Modern business of to-day is very largely conducted by means of the telephone and the typewriter. It has long been felt that if these two giants of industry could be combined and efficiently operated as one unit, we would have made long strides in furnishing the business world with the last words in telephony. After years of study and research work, we feel that we are now able to furnish to our patrons a machine that will efficiently combine these two. This machine is known as the Telephone-Typewriter.

. . . . .

"This is not a new and untried service. For a number of years it has been in daily use by modern business organizations for the rapid and constant transmission of typewritten communications between the executive office—branch offices—warehouses—mills—factories located in distant cities, by the Long Lines Department of the American Telephone and Telegraph Co. in transmitting official communications to all of their offices located in principal cities, and by the Associated Press in accurately and expeditiously distributing current news simultaneously to its newspaper clients.

"Messages can be typewritten in your office and come out at one or more of your local or distant offices with a home record. No operator or attendant is necessary at the receiving end.

"It will do practically anything a typewriter can do and can be operated by anyone who can operate a typewriter.

"This service is now being used by a number of modern business organizations, Press Associations and newspapers with very satisfactory results in the handling of messages, letters, routine matters, such as operations, administration, sales, purchasing, statements of stocks on hand, shipments, orders, quotations, accounting and for the dissemination of news.

"This service may also be used for conference purposes between groups at different offices, locally or in distant cities, thus effecting the saving of a great amount of time and expense incurred by travelling.

"Your branch office is no farther away from you than the telephone typewriter."

. . . . .

"Telephone Typewriter Service will be found dependable and economical as an adjunct to the telephone for the transmission of communications in factories, banks, hotels, and mail-order houses; between the sales, order, credit, accounting, and shipping departments and the executive offices of an establishment; accurately and privately without loss of time or error in giving or taking instructions.

"We have established a Telephone Typewriter Service department and will, without charge, make a study of your communication requirements to ascertain if the Telephone Typewriter Service will be advantageous to you in the conduct of your business."

A skeleton map is given showing combination circuits for the telephone typewriter service within the city of Chicago and nearby territory. Five circuits are shown, each connecting in series from seven to nine city and suburban centres. One line, for instance, connects the General Office in Chicago with branch offices, Factory, Maywood, Melrose-park, Wheaton, West Chicago, Aurora and Elgin. The illustrations show the Morkrum typewheel teletype, which prints on a tape at 40 words a minute, and the Morkrum typebar page teletype which prints on sheets of paper at 60 words a minute. The pamphlet concludes with the statement: "Our telephone typewriter department will appreciate the opportunity of calling on you and explaining the service more in detail."

The publication of such a booklet by a great concern like the Bell Telephone Co., and the corresponding movement by the Western Union, show that this paper cannot be dismissed as idealistic dreaming.

Assuming that teletype exchanges are successfully established by the Western Union and the Bell Telephone Co. in the leading cities of the United States, then it will be a comparatively short step to link up these teletype

exchanges by trunk telegraph wires all over America. Of course, in the case of the Bell Telephone Co., telegraph circuits superposed on its telephone lines will be used, and various systems of multiplexing the trunk wires will also be put into operation more extensively than now.

(7) *Some results.*—The result of this development will be that a business man in New York, wishing to communicate with a business man in San Francisco, will get through to his teletype exchange and be connected to his San Francisco correspondent, with a certain amount of delay similar to, but less than, that which takes place in putting through a telephone trunk call. Once connected, a typist in his office will teletype the business communication, and in many cases an immediate answer will come back on the teletype. In this way business will be linked up directly to the telegraph network, just as it is now linked up to the telephone service, and the present telegraph delays will be eliminated. There will be much greater accuracy than with the telephone and there will also be the advantage of much cheaper rates of communication than are possible with the telephone service; multiplexed telegraph wires being far cheaper than telephone wires. In fact, in the case of an immense concern like the Bell Telephone Co. the use of its telegraph circuits in this way will really be the utilization of a by-product of its telephone business. The same remarks apply in the case of the British Post Office and other administrations supplying telegraph and telephone service. The economies that will be effected by cutting out all telegraph labour, and by transmitting and printing direct, have already been explained.

One remarkable idea in connection with the proposed teletype exchange scheme hinted at in the Bell Telephone pamphlet is its use for conferences, because the teletypes at each point could be linked up so that all would record the messages transmitted at each station. Half a dozen business men, 10 or 20 or 1 000 miles apart, could get together by teletype for a conference at very short notice. The teletypes in each office would record the minutes of the conference, including the discussion and the full text of the resolutions passed or decisions arrived at, and each member of the conference would have a complete typed record of the proceedings in his office. Also, the conference would be secret. There would be no overhearing or eavesdropping. The teletype language is spoken and understood only by teletypes, and the code-bars can be mixed at will to scramble the messages and make them doubly secure against overhearing by outsiders. There is something deeply impressive about this idea of a conference taking place between men hundreds or even thousands of miles apart, with no sound but the slight tapping of the typebars, and the men in silence, each alone, watching the words being recorded, or transmitting on his keyboard. Not even a secretary need know about it. The saving of the precious time of business or political magnates would be great, and the acceleration of the business, which could not otherwise be transacted until the members of the conference had actually met after much delay and railway travelling, would be important. Vital decisions might be made in this way, possibly a week sooner than would otherwise be possible. Take, for instance, the British Government; an urgent meeting of the Cabinet could be held and decisions arrived at with the members of the Cabinet scattered all over the country. Members of Parliament could confer with their constituents, and even international conferences could be held in this way with every advantage of "secret diplomacy." The only parallel to such a teletype conference would be a wireless telephone conference between heads of Governments, to which all the world would listen in, and we should have "open covenants openly arrived at."

Returning again to realities, the new telegraphy with its cheap and quick long-distance communication will be an immense boon to the industrial and financial world, and many interesting practical results of political and social importance will flow from it. Two may be briefly referred to as illustrations. One will be the upsetting of the present balance of telegraph and telephone interests in the United States, the probable result being consolidation under the control of the Interstate Commerce Commission. The new telegraphy will lead inevitably to competing teletype exchanges in each city. This development will be as great a nuisance as competing telephone exchanges, and the public convenience will be best served by consolidation, the result being a telegraph and telephone organization in the United States by far the largest and most remarkable in the world. Another result will be increased impetus to the extension of the Garden City movement and decentralization. Obviously the great book-keeping industry can be carried on in low-rented premises in pleasant surroundings in the country just as well as in London city offices, dirty, smoky and dark, and costing exorbitant sums for rent. The teletype and the telephone bring the Garden City book-keeping factory alongside the London city office, which will contract into a showroom and calling-place for visitors. This process of decentralization in connection with factory work has been going on for years and the teletype and telephone will extend and accelerate the process.

As these great changes will be brought about by the start-stop telegraph printer, it will be realized that this is a machine of outstanding commercial and political importance.

(8) *How the teletype exchanges will work.*—Just as in the case of the telephone service, there will be private-branch teletype exchanges, and these will of course connect up to the main telegraph network of the country through the city teletype exchange. In Chicago, for instance, the Morrison Hotel is equipped with 32 of the little tape teletypes, forming an internal intercommunicating system in all respects like a private-branch telephone exchange, and other American hotels are being fitted in the same way. Naturally, these private-branch exchanges will be linked up with their respective city teletype exchanges and in this way put in telegraphic communication with the whole of America and, in the course of time, via the new 300-words-a-minute Atlantic cables, also with Europe.

It is possible that the number of teletype subscribers in one city may not, for many years, be more than one exchange could handle, and in that case the teletype

exchange would be situated in the chief telegraph office of each city. This, however, would depend on the size of the city and the length of the local lines to connect subscribers to the teletype exchange. It is a detail that will be settled by local circumstances. In London, for instance, there will probably be teletype sections in most of the telephone exchanges, with a big central teletype exchange at the Central Telegraph Office.

This telegraph service will be paid for just as the telephone service is paid for. There will be a local message rate, and time and distance rates for trunk or long-distance messages. Fortunately for this new development of the telegraphs, most of the problems have already been worked out in connection with the telephones, and telephone technique will be used in the teletype exchanges and wherever else it can be employed with advantage. The mechanism of telephone exchanges, with some modifications, will do equally well for teletype exchanges. A subscriber will be able to ring up any other subscriber, with all the usual "engaged" and other signals; but the teletype subscriber will have an advantage that he cannot have now on the telephone trunk service. Suppose he is a London merchant. He will be able to ask the Central Telegraph Office in London to put him through to Glasgow, and he will be put through exactly as now in the case of a trunk telephone call—with this important difference, that the delay in getting through will probably be small in the case of the telegraph service, perhaps not more than a minute or two, or even with no delay at all, because there will be far more "channels of communication" available to Glasgow and other cities than would be financially possible in the case of the telephone. A single telegraph wire will give at least six separate channels, compared with one channel of communication on two telephone wires. Take, for instance, some results obtained by the Western Electric Co. on four aerial wires between Chicago and Omaha, 450 miles. These four wires gave three telephone circuits, four earthed telegraph circuits and no less than 20 two-way carrier telegraph circuits, or more than six "channels of communication" on each wire.

In London alone about 18 minutes' delay would be cut out by getting direct in this way to Glasgow, and even if the message were sent by the customer by telephone as a "phonogram" it would still go to the phonogram room, where it would be written down and sent "circulating" until it reached the Glasgow circuit. On the average in a provincial telegraph office in Great Britain the "transit time," that is to say, the time elapsing from the handing over of a telegram by the public until it reaches the circuit over which it is to be transmitted, is about 5 minutes, and in London about 8 minutes. The average "circuit delay," that is to say, the time that a telegram has to wait its turn at the circuit before being transmitted, is about 10 minutes. This circuit delay corresponds to the delay in getting through on a trunk or long-distance telephone line. Hence, in provincial offices there is an average delay of 15 minutes from the time a message is handed in to a telegraph office until transmission begins over the telegraph line. In London this combined delay of transit time and circuit delay averages 18 minutes. There is also telegraph messenger time, which may run into anything from 5 minutes to half an hour or more, depending on the size of the staff of messengers available and the distance to be traversed. The aim of the new telegraphy is to cut out all these delays.

With teletype exchanges in operation, manual "circulation" of telegrams will give place to manual switching and, finally, to automatic switching. That is to say, the handling of telegrams will be greatly reduced, and instead of many telegrams being rewritten several times in the course of their wanderings, they will go straight through to their destinations, like the modern loaf of bread, without being touched by human hand. At present some telegrams have actually to be rewritten four or five times. A message handed in at a suburban office in London is rewritten at the Central Telegraph Office and then telegraphed, say, to Glasgow, where it is once more rewritten and sent to another suburban telegraph office, and once more rewritten before being delivered by a message-boy.

Obviously, cutting out the circulation of telegrams will eliminate great waste of time and labour, especially in big cities like London. Telegrams received at the Central Telegraph Office in London have to go through an elaborate journey before reaching the London end of the telegraph lines over which they are to be transmitted. They are taken in and dealt with by counter-clerks, blown through pneumatic tubes, shuffled at distribution tables, pigeon-holed, and then taken to their respective circuits for transmission. Delay also takes place at the receiving office. There are similar delays in large offices where telegrams have to be retransmitted. They have to be circulated until they reach the right point for retransmission. The start-stop printer and the teletype exchange will short-cut all this delay and waste of labour. Also the ridiculous time- and labour-wasting process of checking and counting the number of words in telegrams at every stage, unavoidable by present methods, will disappear. One count will be sufficient, and when transmission is direct from the sender to the receiver of the message, there will be no counting at all, but a charge by time and distance.

With a start-stop printer and the teletype exchange, the subscriber in London would communicate, clear of all obstructions, direct from his office in London to the office of his correspondent in Glasgow, who could, if the message permitted, reply at once. Obviously this should be considerably cheaper than sending a telegram in the ordinary way, because no telegraph operators would be required. The work of sending the telegram would be done by a typist in the merchant's office, and all the handling of the message in "circulating" it to the Glasgow circuit would be cut out. The cost and delay of the telegraph messenger would also disappear. In addition, as the cost of the telegraph line used in sending the message from London to Glasgow would only be about one-twelfth of the cost of a telephone circuit, the message ought to cost much less than a telephone message to Glasgow. Also the duration of a teletype call could be reduced, compared with a telephone call, from, say, 3 minutes to 2 minutes. The latest start-stop printers work well up to about

80 words a minute, and a good typist can do 60 words a minute easily. Hence 120 words could go through in 2 minutes, or 10 times as many words as the usual 12-word telegram for which the Post Office charges a shilling. Clearly there would be great economy to the Post Office through the adoption of this form of telegraphy, and time- and distance-rates could be arranged that would be profitable to the Post Office and yet attractive to business men.

Of course, speaking in a general way, there is nothing new in all this, and therein lies good hope for success. There is nothing idealistic about it, and it is only a slight extension of what is already done. The telephone does it already, and substituting a telegraph transmitter and receiver for a telephone transmitter and receiver ought not to disturb the most conservative mind. Further, there is nothing particularly new in this, even from a telegraphic point of view. There are telegraph concentrator systems in all important telegraph offices, now used to concentrate and save labour, but which may be regarded as germs of telegraph exchanges. There is also the London intercommunication switch designed by the present Engineer-in-Chief of the British Post Office, Colonel T. F. Purves, and installed in 1902.* This may be described as an official and not a public telegraph exchange. It is a real telegraph exchange interconnecting London local telegraph offices; but it does not attempt the final linkage to business firms, because it uses the morse key, an instrument not commercially practicable in such cases. Colonel Purves's book contains some very interesting information on the subject of "through-switching" of telegraph exchanges. It was carried out in England as early as 1854, but it was used to connect telegraph office to telegraph office and not subscriber to subscriber. The telegraph exchange plan was used and abandoned by other administrations many years ago, but Belgium persevered with the arrangement and it is still in use in that country for morse telegraph working. Briefly the scheme is approximately as follows:—Station A, connected by direct wire to station B, has a telegram for, say, station F, whom he calls on his line to B. There may be more than one route from B to F, via, say, C, D, E, or G, H, J; the more appropriate route is selected by B and the call is passed on until F replies to A.

As a matter of fact the London intercommunication switch, after having been in use for 20 years, has gradually been killed by the competition of the telephone, and it is understood that the British Post Office proposes to abandon it. The intercommunication switch was primarily designed to link up about 200 local London telegraph offices so that telegrams could be transmitted direct between any of these local offices by way of the central switching exchange. Obviously this is not a subscriber system like a telephone exchange, and it does not possess the great advantage of the telegraph over the telephone of cheap long-distance facilities. It is a telegraph exchange attempting to compete with the telephone on ground most favourable to the telephone. Naturally the telephone has gradually drained away the traffic until there is very little left for the intercommunication switch to handle. People will not spend a shilling for a 12-word telegram in London with about an hour's delay, when they can send and receive 1 000 words with no delay and for less than twopence by telephone. A local London service of threepenny telegrams might revive the intercommunication switch, especially if combined with start-stop printers. Also to extend the area of service, so as to bring in the advantage to the telegraph of longer lines, might help; but it is on the subscriber, or what might be called the "direct user," that the success of the new telegraphy will depend.

It is necessary to point out the weaknesses of the London intercommunication switch, because its want of success will probably be used as an argument against the new telegraphy. A little space must therefore be devoted to it. Apart from the deadly competition of cheap short-line telephones at about one penny per message and answer, a telegraph exchange relying on the morse key and sounder cannot hope to be a success; first, because average private users cannot afford the expense of keeping a morse operator, although they can and do habitually keep girl typists; and secondly, because a morse operator sending needs a morse operator receiving. The start-stop printer solves these two difficulties. It supplies the private subscriber with a telegraph machine which his typists can use after a few minutes' practice and without additional expense for labour, and it substitutes an automatic and reliable machine in place of the receiving morse operator. In fact the morse operator will not be required. One typist can attend to half a dozen teletypes if the traffic is not heavy, and the receiving typist will be able to send at any moment when the line is free. There is also a possibility of some kind of duplex working, giving simultaneous communication each way on the one wire.

At present, in the case of these local London telegraph offices linked up by the intercommunication switch, the Post Office, and not subscribers, has to pay the wages of the morse operators at both ends of the lines. The teletype exchange with private subscribers will relieve the Post Office of payment of wages for a gradually increasing portion of the telegraph traffic. Another point not to be forgotten is that the start-stop printers will enable the typists to do about double as much work as with morse key and sounder, and a receiving typist will not be required for each printer. The engaged signal has seriously reduced the economic efficiency of the intercommunication switch, because paid Government operators are kept waiting. With private subscribers any loss due to engaged signals will not fall on the Government any more than in the case of telephones. In the case of a typist attending to several teletypes in a local telegraph office, acknowledgment of receipt of messages presents some difficulties, but a bell or a lamp signal at the end of messages would warn and guide the attendant in giving acknowledgments of receipt of messages without unreasonable delay even if half a dozen printers required attention.

Another plan would be to use the reservoir effect obtainable by means of receiving-tape perforators and retransmitters. This, however, introduces complexities,

* See "Telegraph Switching Systems," by T. F. Purves.

to say nothing of perplexities, and probably the best plan is the "engaged" signal if a message cannot be accepted at once.

It is to be noted that even the connecting-up of outside customers to telegraph offices is not new. The use of the Steljes step-by-step printer in this way is very old in England, and a similar arrangement has been in use in Germany for years, the little Ferndrucker of Siemens and Halske being very largely employed for the purpose. This, however, like the Steljes, is merely a step-by-step printer like a stock-ticker, provided with a typewriter keyboard, and the speed is low, about 25 words a minute; and, being on the step-by-step principle, neither the Steljes nor the Siemens Ferndrucker is satisfactory for working much beyond city limits. In "Telegraph Switching Systems," Colonel Purves mentions that ABC telegraph exchanges between ABC subscribers for direct telegraphy were in actual use in England in the late seventies, but the telephone swept them away. This is of real historical interest, because it shows that the telegraph would long ago have developed on the lines indicated in this paper if modern printing-telegraph machinery had been available. As it was, the telephone, when it arrived, swept all before it. Whether the telegraph can recover lost ground now that the machinery is available, is purely a commercial question.

The really new feature of the service about to be put into operation in America is the use of start-stop printing-telegraph machines capable of high speed, 40 to 80 words a minute, tape-printing or page-printing, and able to work with ease over thousands of miles, and capable also of linking up with the multiplex telegraph network of the country, and with the potentiality of sending messages automatically all over the world. That is quite new and of the greatest importance, and it is the start-stop printer that has made this development possible.

(9) *Linking up the telegraph network.* I have referred to the possibility of linking up the start-stop printers with multiplex trunk circuits. A good deal of work has been done in this direction by the Western Electric Co., and several years ago it exhibited in London an installation of its multiplex system with start-stop printer extensions from various channels. In a description issued in the course of its demonstration, the company mentioned that the start-stop printer had been in duplex operation on a circuit 1 000 miles long between New York and Chicago with one girl operator at each end. This circuit was obtained by superposing on a telephone line, and the daily average load for 9 hours was 22 000 words, or about 1 000 messages. The company also mentioned that it is possible to provide intercommunication between a number of offices by means of the start-stop printer when working simplex, and also to use selectors by means of which any one of a number of stations may be called, the printers at the other stations remaining idle while a message is being printed at the selected station. These facilities can of course be supplied by any other modern start-stop printers such as the Morkrum teletype, the Kleinschmidt, the Creed direct printer, or the Siemens and Halske.

The Western Electric Co. has some interesting patents on methods of linking up start-stop printers with channels of multiplex installations. There is, for example, British patent 165783, showing various branching arrangements for connecting up several cities with both forked multiplex and start-stop printers. Fig. 1 in the above patent, for instance, shows a Y-forking arrangement comprising three terminal multiplex distributing stations arranged for four channels from each terminal multiplex station, through a repeating station, to each of the other terminal multiplex stations, and also illustrates how one arm or channel of the multiplex distributor at, for example, St. Louis, may be extended by means of start-stop equipment to two outlying cities or stations. It is also pointed out that any or all of the channels of each terminal multiplex station may be extended, if desired, to an equal number of distant or outlying stations by means of start-stop equipment.

In France, forked and series working with the Baudot multiplex has been in use for many years, and the French have wonderful methods of linking up various cities on one wire by the multiplex. The Western Union has likewise been doing a good deal of work in this direction, and those who are interested will find it fully dealt with and illustrated by clear diagrams in Mr. H. H. Harrison's book on "Printing Telegraph Systems and Mechanisms"; but, to refresh the memory of those who are familiar with the subject and to enlighten those who are not, in Fig. 2 two diagrams from the Western Electric patent above referred to, with the addition of start-stop printers to each channel and teletype exchanges in the cities, are given.

Fig. 2 will help us to realize the enormous extension of telegraph facilities rendered possible by the start-stop printer. It represents two wires from New York via Pittsburg to Chicago, one of the two wires having a branch from Pittsburg to St. Louis. These wires are equipped with multiplex printing-telegraphs working quadruple-duplex, giving four channels of communication simultaneously each way, solid lines representing channels working in one direction and dotted lines channels working in the other direction. The small rectangles marked M indicate sending and receiving sets on the multiplex. The rectangles marked S are start-stop printer extensions linking up to the multiplex channels. The rectangles SS are a number of start-stop printers in series on one wire, selective callers enabling any one or more of the SS sets to be called up and communicated with. The teletype exchanges explain themselves. To complete the picture, subscribers are needed. They are scarce at present and hard to convince, but their numbers will grow geometrically as the facilities extend, just as they did in the case of the telephone.

A great advantage that the telegraph possesses over the telephone is that a telegraph message can be stored up at any point where there may be a "bottle-neck," until its turn comes for transmission. A telegraph operator usually has several telegrams in hand, which he transmits one after the other. They wait their turn. A telephone message cannot wait. In a vast telegraph network such as that contemplated in this paper, the bottle-neck is a factor for which provision must be made. The excess in the supply of telegraph circuits will not

last for ever, and in any case there will be certain points where delay will be liable to occur at times, especially during rush hours. The flow of telegraph traffic is very irregular, and there will be advantage in having reservoir mechanism at bottle-neck points, such as ocean cable terminals. Hitherto the receiving tape-perforator has been neglected by telegraph traffic managers; but it is possible that the receiving perforator will come into its own in the new telegraphy. A business man in New York will dictate a telegram, a typist will transmit it to the nearest teletype exchange, and it may succeed in going direct as far as Chicago, and all channels west of Chicago may be engaged for a time. In that case the message might be stored up as perforated tape ready for transmission to San Francisco as soon as a channel is available. Otherwise the messages, in such cases, could be received on printers and retransmitted in their turn on typewriter keyboards. suddenly called upon to send a message on the teletype for her employer. Quite obviously your teletype exchange would only be for big business firms and companies, banks, railways and the like. For the thousands and thousands of small men it would be useless. It would not pay them to use a teletype for one or two telegrams a week."

The best reply to this supposed criticism will be to quote a few figures. The financial advantage possessed by the telegraph when distance becomes an important factor is a powerful argument in favour of the long-distance telegraph and against the long-distance telephone, and the telegraph administrations will be glad to increase their profits by reducing their expenditure on wages by throwing the burden of transmitting and receiving telegrams on to the business community, and the business community will be glad to shoulder that burden in return for the boon of quick telegraph service.

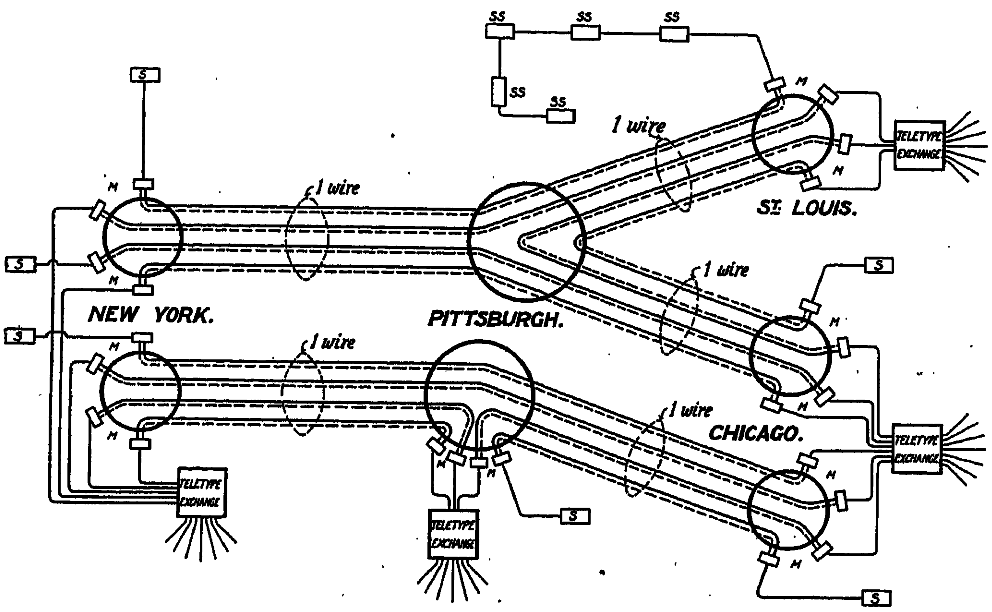


FIG. 2.—Diagram of multiplex printing-telegraph combined and extended by start-stop printers, single and in series, and with teletype exchanges.

Naturally there are many difficulties in the way, including human nature and established routines, and there are also serious arguments which have to be met. For instance, I can imagine the British Post Office saying to me: "Three-minute calls on your teletype exchange would be only 20 telegraph messages an hour per channel, and there is the loss of time in calling, answering calls, getting through, giving the line to the subscriber and disconnecting, which would diminish the output to perhaps 15 messages an hour, or even less. We can quite easily send 60 messages an hour by our present methods, as long as there is enough traffic, and at times we send 80 and 90 and even 100 messages an hour per channel. If your teletype exchange cuts down the average to 15 messages an hour, we shall have to charge more. Also our professional operators steadily employed on telegraph circuits will send far more messages than a girl typist There is every indication that there is money in the new telegraphy, and if that is the case the matter is settled.

It must not be forgotten that the telegraph administrations and companies lease telegraph wires or "channels of communication" for long terms, 6 months or a year, and they will be glad to lease telegraph wires for 3 minutes, just as they lease telephone wires, if they can make money by doing so. The financial case for the new telegraphy will be realized after a little study of the table on page 262 giving the British Post Office annual charges for telegraph and telephone wires.

Taking, first, London to Birmingham, roughly about 100 miles, the Post Office will lease a complete telegraph wire during the day for a rental of £685 a year. There is no difficulty in getting six channels each way on one telegraph wire from London to Birmingham. Hence dividing £685 by six we get a rental of £114

a year per channel. Dividing this by 300 days in the working year, we get 7s. 7d. per day. Taking the business day at 8 hours, we get a rental per hour of a trifle under 1s., or only 0·2d. per minute. Assuming that the active time of communication is 3 minutes and that the time spent in connecting and disconnecting is 3 minutes, or, in all, 6 minutes per call, the rental would be only a trifle over 1d. for 6 minutes. Even if the Post Office tripled this rate and charged 3d. for a 3-minute teletype talk between London and Birmingham with a "no delay" service, it would be regarded by the business community as a godsend. The minimum for a London—Birmingham telephone call of 3 minutes is 2s. There is a big difference between 3d. and 2s., and the difference is still greater if we deduct the cost of postage, 1½d., which is saved in each case by using the telegraph or telephone instead of the mail. It becomes 1½d. extra for the teletype call of 3 minutes transmitting at least 100 words, and 22½d. extra for the telephone call, an advantage of 15 to 1 in favour of the telegraph, even over only 100 miles.

Now working backwards, the Post Office is to get 3d. for 6 minutes (a 3-minute call and 3 minutes con-

Approximate Annual Rentals for Lines.

	London to Birmingham	London to Manchester	London to Glasgow
A telegraph wire, but not including apparatus ..	£ 685	£ 1 120	£ 2 415
A telephone circuit with apparatus	905	1 520	3 350

necting) on one channel between London and Birmingham. This is 2s. 6d. per hour, or £1 a day of 8 hours, or £6 a day for the six channels on one wire, or £1 800 rental for the year of 300 days. This is, of course, on the assumption that the wire is kept busy with calls every 6 minutes. Actually it is possible to divide up a wire between London and Birmingham into at least 12 channels each way, so that there would be a future possibility of penny teletype calls between London and Birmingham, exchanging about 50 words each way. In other words the business community will get an extremely cheap and quick telegraph service and the Post Office will get a greatly increased rental for its telegraph wires and will save the wages of operating staff at present employed handling telegrams. £1 800 a year should leave ample margin for the wages of the exchange attendants and for maintenance and other charges.

Now take London–Manchester, about 200 miles. The Post Office annual rental for a telegraph wire is £1 120. Five channels can be provided easily each way on the one wire, making the annual rental £224 per channel. Dividing this up as before we get 0·375d. per minute. Allowing 6 minutes per call as before, we 2¼d. per call, and, tripling this as before, the call d cost a trifle under 7d. This charge would give 'ost Office an annual rental of £3 500 for a London–hester telegraph wire. This again is on the assumption that there is a call every 6 minutes. A 3-minute telephone call to Manchester from London would be about 4s., compared with 7d. Taking London–Glasgow, the rental is £2 415, and five channels each way can be easily secured. Hence, dividing by five, we get £483 a year rental per channel, or 0·8d. per minute, or 4·8d. for a 6-minute call (3 minutes communicating and 3 minutes getting through). If we increase this to 1s. as the rental for the 6 minutes, the total rental would be £6 000 a year for the five channels on one wire. A 3-minute telephone call to Glasgow would be about 8s. At present a shilling telegram from London to Glasgow would contain only 12 words, and it would take about an hour on the journey from sender to recipient and another hour for a reply. For the same shilling the new telegraphy would handle at least 100 and possibly 180 words, or a message and reply with little or no delay. At present the Post Office is working at a loss when charging 1d. a word, and at present the 180-word message would cost 15s.

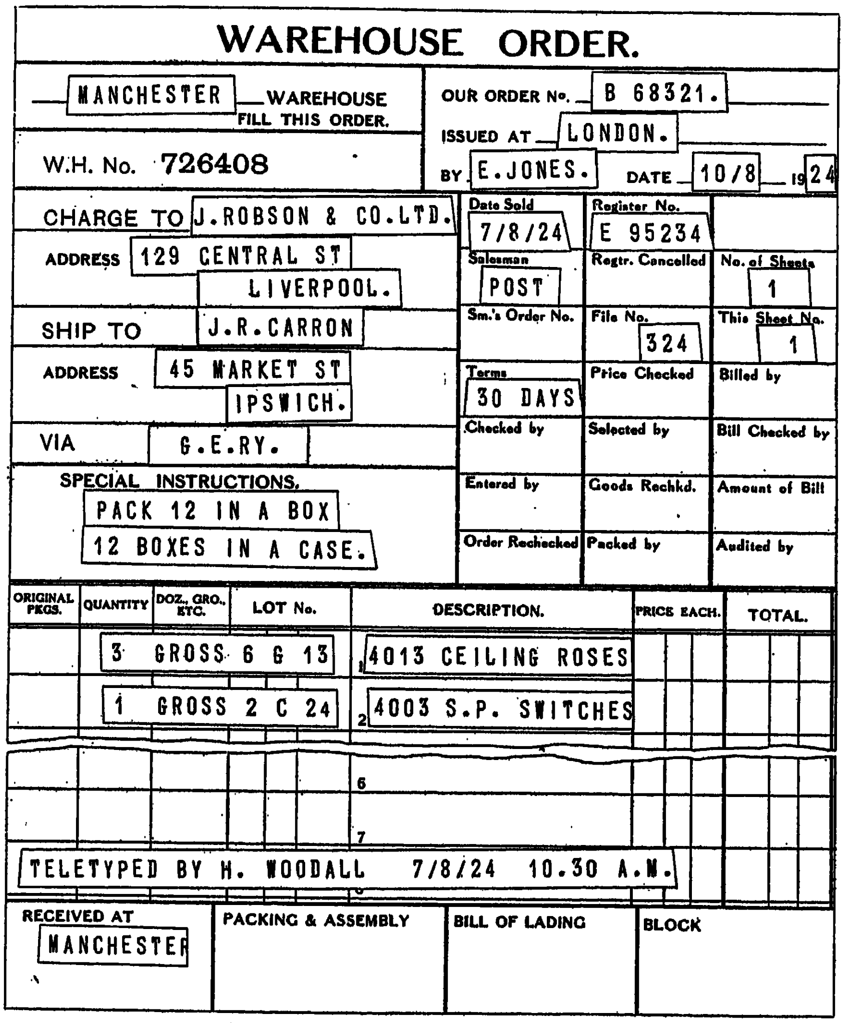
Apart from the direct saving due to the new telegraphy, the wealth of the community would be increased by the speeding up of business resulting from the improved telegraph service. It is all a question of whether the scheme of public teletype exchanges is economically sound. It appears to be sound, but time and experience will tell in due course. There is no millennium for telegraphy; but as long as we do not expect too much from telegraph machinery and human nature, we have good reason to be hopeful about the great improvement in the telegraph service that will take place within the next 25 years, thanks to the multiplex printing-telegraph, the start-stop printer and the teletype exchange.

(10) "*Emptying the mail-bags.*"—An important aspect of the new telegraphy is where the increase of traffic is to come from, that will be necessary to pay for the new developments. Of course the new facilities will create a large volume of new traffic beyond the small annual increment due to growth of population and civilization; but, in addition, the increase of telegraph traffic will come by diversion of a certain amount of traffic from the telephones, and by what Delany used to call "Emptying the Mail-Bags." This is what American publicity men call a slogan; but it is a very poor one, because it is an impossible ideal, and the maximum that the telegraphs can hope to effect is a slight lightening of the mail-bags. Even 1 per cent of letters diverted from the Post Office would result in a great accretion of telegraph traffic.

The mails consist very largely of circulars, newspapers, printed matter, invoices, receipts, postal and money orders, cheques, drafts, securities, advice and receipt notes, waybills, bills of lading, drawings, blueprints, maps, plans, photographs—in short all the vast variety of business documents which cannot be telegraphed. There is also an enormous volume of private and domestic letters, of which only a minute proportion would ever be telegraphed, unless telegraphy became so excessively cheap that it could compete with the penny stamp and the postcard. There remains, however, a large volume of ordinary business correspondence which could be profitably sent by telegraph if the rates were low,

though not so low as the penny post. We should have to educate the business man up to paying more and the telegraph administrations to charging less, so as to bridge the gap and enable a portion of the mails to be poured through the telegraph wires.

It is impossible to say even to what very limited extent the mail-bags can be depleted by the telegraph; but anything in letters and figures can be transmitted, and even complicated formal printed documents can be filled in by telegraph if a tape-printing telegraph is used. An illustration of this is given in Fig. 3, and be telegraphed. The proportion of business letters, otherwise telegraphable, which must go by post on account of enclosures is not known, but the matter was looked into by a London firm in connection with their departmental correspondence. This firm, with offices in London and works 30 miles away, have a private telephone circuit connecting their London offices with their works. This telephone circuit is overloaded with traffic, and a proposal to superpose a teletype circuit on the telephone circuit proved attractive to them. Not only would the carrying capacity of their private


WAREHOUSE ORDER.

MANCHESTER WAREHOUSE FILL THIS ORDER.

OUR ORDER No. B 68321.

ISSUED AT LONDON.

W.H. No. 726408

BY E. JONES. DATE 10/8 19 24

CHARGE TO J. ROBSON & CO. LTD.

ADDRESS 129 CENTRAL ST LIVERPOOL.

SHIP TO J. R. CARRON

ADDRESS 45 MARKET ST IPSWICH.

VIA G. E. RY.

SPECIAL INSTRUCTIONS. PACK 12 IN A BOX 12 BOXES IN A CASE.

Date Sold 7/8/24 | Register No. E 95234

Salesman POST | Regtr. Cancelled | No. of Sheets 1

Sm.'s Order No. | File No. 324 | This Sheet No. 1

Terms 30 DAYS | Price Checked | Billed by

Checked by | Selected by | Bill Checked by

Entered by | Goods Rechkd. | Amount of Bill

Order Rechecked | Packed by | Audited by

ORIGINAL PKGS.	QUANTITY	DOZ., GRO., ETC.	LOT No.	DESCRIPTION.	PRICE EACH.	TOTAL.
	3	GROSS	6 G 13	1 4013 CEILING ROSES		
	1	GROSS	2 C 24	2 4003 S.P. SWITCHES		
				6		
				7		

TELETYPED BY H. WOODALL 7/8/24 10.30 A.M.

RECEIVED AT MANCHESTER | PACKING & ASSEMBLY | BILL OF LADING | BLOCK

FIG. 3.—Printed-form tape telegram.

the bits of teletype tape pasted all over the printed form will be noticed. A page-printer could not do this.

Signatures, on the other hand, are hopeless in spite of telautographs and copying telegraphs, and telegraphic transmission of pictures and drawings will seldom pay.

There is, in addition, one interesting obstacle in the path of transmission of letters by telegraph, about which more may be heard in the future, and that is "enclosures." Many business letters which could be telegraphed with advantage contain cheques, bills of lading and various other business documents, which cannot wire be increased, but orders and other correspondence that now reach the factory on the following day would arrive by telegraph by the aid of the teletype in a few minutes, thus saving a day in the case of a factory 30 miles away; and time is money.

Upon investigation, they found that 40 per cent of their correspondence with their factory contained enclosures which could not be telegraphed, leaving 60 per cent that could be handled by the teletype. This is instructive, but not sufficiently generalized to be any guide to the average contents of the mail-bags. The

proportion of letters that could be telegraphed is well worth investigation by inducing a number of business firms of various kinds to look into the matter and prepare statistics. Also it is obvious that the proportion of letters that it would pay to telegraph would be still smaller. Many firms could no doubt be induced to prepare statistics on this point also. In this way a fair estimate could be made of the extent to which the new telegraphy may benefit at the expense of the mail-bags.

(11) *The first steps.*—The problem of making a beginning with the new telegraphy deserves a little consideration. It will have to start on a small scale, because administrations cannot be expected to spend hundreds of thousands of pounds to install teletype exchanges in all leading cities, and then spend more money in canvassing for subscribers to the new service. There must be healthy growth from small beginnings. It will probably start very much as the telephone service began. A start has already been made in connecting business firms and banks to the Central Telegraph Office. The Dutch Government has installed a considerable number of teletypes for this purpose, and the British Post Office is beginning to do the same. If this service grows it will lead to a concentrator system, because subscribers' lines will not always be busy, and by means of a concentrator switch the traffic can be handled by a considerably smaller number of teletypes at the Central Telegraph Office than the number of subscribers. It seems reasonable to suppose that this arrangement will gradually extend to switching subscribers direct to the particular circuits over which their telegrams would have to be transmitted. The British Post Office already has teletypes in use on long lines, and "through switching" would appear to be inevitable in the course of time.

Another line of growth has already been indicated in connection with the offer of the Western Union and the Bell Telephone Co. of telegraph typewriter service on the private wires of private firms. These private lines will naturally be linked up in due course, with resulting growth of the new telegraphy.

Part 3.

The Start-Stop Printer.

(1) *Various machines and what they must do.*—It remains now to give a general idea of what is meant by the title "Start-Stop Printer." As far as possible details will be avoided, because this paper is being written not for telegraph engineering specialists but for the vast number of people who are mainly concerned about better telegraph service. Before beginning this last section of the paper, however, I may also explain that I have refrained from expressing any opinion about the relative merits of the various machines now on the market or being developed. They are the product of a vast amount of ingenuity and research and practical experience, and time will in due course settle which is the best, or what particular combinations of the ideas materialized in these machines will prove to be the most suitable for various classes of work.

The conditions to be fulfilled by a successful start-stop printing-telegraph may be set out as follows:—

(*a*) It must be a start-stop printer; that is to say, it must start operating as soon as a key is depressed on the keyboard, and it must stop as soon as a letter has been printed.

(*b*) Most of the successful machines have a mechanical distributor and a single recording magnet.

(*c*) It must have the standard typewriter keyboard, with easy touch.

(*d*) It must have a speed of from 40 up to 80 words per minute.

(*e*) It must use the five-unit alphabet.

(*f*) It must be able to work over any distance, from 50 feet to 5 000 miles.

(*g*) The option of tape- or page-printing is desirable.

(*h*) For speeds above 50 words per minute, Western Union experience indicates that typebar machines are best; but good results are being obtained by some of the typewheel printers.

(*i*) It must be simple, compact, strong and durable, and able to print at least 5 million words without an error.

(*j*) It must be able to run for at least one month without attention, apart from the supply of fresh paper and ink.

(*k*) Maintenance must be possible without highly skilled labour.

(*l*) The manufacture must be strictly on the interchangeable mass-production basis, to ensure cheap maintenance, quick repair and moderate prices.

(*m*) It should be possible to stop the printer completely and shut off all power at out-station B from head-station A, and start it again from station A.

(*n*) It would be desirable to have a universal printer which, with comparatively slight modifications, could be used on multiplex circuits, or as a start-stop printer with typewriter keyboard, or with perforated-tape transmission, or as a rapid stock-ticker; but there are grave difficulties in the way of making such a machine.

With the exception of the first-mentioned in the following list (which, after being widely used in America for 15 years, is now being superseded by a more recently developed machine of the same company), the only machines at present on the market which attempt, more or less successfully, to fulfil these conditions are the following:—

Start-Stop Printers.

	Approximate speeds *
(i) Morkrum typewheel page-printer (Blick typewheel), the first of the commercially successful start-stop machines. Page-printer only ..	70 w.p.m.
(ii) Morkrum typewheel teletype; the first start-stop machine to achieve wide success outside the United States. Tape-printer only ..	40 w.p.m.

* w.p.m. = words per minute.

(iii) Western Electric start-stop printer. Page-printer only .. .. 60 w.p.m.
(iv) Kleinschmidt direct printer. Tape or page-printer .. .. .. 80 w.p.m.
(v) Siemens and Halske "Pendeltelegraph." Tape-printer only .. 40 w.p.m.
(vi) An improved machine by Siemens and Halske based on Siemens automatic system.. .. .. 80 w.p.m.
(vii) Creed direct printer. Tape- or page-printer .. .. 80 w.p.m.
(viii) Morkrum page teletype. Typebar page-printer .. .. .. 65 w.p.m.
(ix) Morkrum model-15 typebar teletype. This is the latest start-stop machine. Tape- or page-printer 80 w.p.m.

(2) *Historical.*—Speaking in a general way, what the Western Union calls the simplex printer is a very old idea, going back to the beginning of telegraphy, and it is an astonishing fact that it is only during the last year or two that real success has been achieved. There have been many pioneers, and scores of simplex printing-telegraph inventions fill the shelves of the patent libraries. They were pioneers, and they all failed for themselves; but not for us, because "by their bones about the wayside we have come to our own." They have guided us on the road, and within the last 2 or 3 years we have arrived.

It might be thought that the complicated automatic and multiplex high-speed printing-telegraphs with their enormous carrying capacities of 100 to 300 words a minute in each direction on one wire, and, in the case of the multiplex, with two to six separate channels each way on one wire, would have developed after the much simpler business-man's printing-telegraph; but the requirements of the business-man's teletype are very severe, as will be realized from the list just given of conditions to be filled by a successful machine of this class. Many beautiful machines have been designed; but for 50 years the Hughes printing-telegraph has been practically the sole one-man machine that would work successfully even in a large telegraph office with skilled attention immediately available, and it is not a start-stop printer. The Hughes would be quite unsuitable as the business-man's teletype for several reasons, the chief objection being that it is a synchronous printing-telegraph. It is also big and clumsy, with a piano instead of a typewriter keyboard, and it requires skilled operation to reach even 30 words a minute, whilst 60 words a minute is far beyond its powers. A girl typist cannot sit down and work it forthwith. The fact that it prints on a tape is not a serious objection, though it is believed that page-printing will be demanded in many cases by the business community. They will want at least the choice of tape- or page-printing to meet their particular needs. What business men require is typewriting at a distance. The need has been known for years, but not the way. Twenty years ago Mr. W. A. Hatfield, one of the engineers formerly employed in the Engineer-in-Chief's Office, G.P.O., repeatedly urged me to make a start-stop printing-telegraph with a direct keyboard; but I was too busy with the Murray automatic and the Murray multiplex printing-telegraphs to attempt any other development work. In any case the conditions of success were not known at that time, and the labours of many men and much capital and years of time were necessary to discover the conditions.

The first really successful machine of this kind was the Morkrum start-stop printer, which was put into commercial service in 1910. It was a typewriter keyboard machine with a typewheel page-printer very similar to the Blickensderfer typewheel typewriter. It came into extensive use in America; but it depended for its operation on a considerable number of magnets and electrical contacts, and it required much maintenance attention. It is therefore being superseded by later Morkrum machines. American as well as French experience appears to indicate that a successful telegraph printer should be, as far as possible, mechanical in its action, and further development in America has gone along these lines.

This resulted in the production of the little typewheel "Teletype," which was put on the market in 1920 by the Morkrum Company and proved highly successful. The teletype is the first machine of the kind that has had a wide sale outside of the United States, and from the date of the established success of this new machine the era of the new telegraphy may be said to have begun.

Kleinschmidt came close on the heels of the successful Morkrum machines, with an extremely clever, direct, keyboard page-printer, very neat and compact in design, which is meeting with considerable success. About the same time the telegraph development engineers of the Western Electric Co. were doing valuable work on the start-stop problem. Their start-stop printer worked well, and amongst other things they designed a most ingenious centrifugal governor for their start-stop printer motor, which is easily the best yet made. The work done in developing arrangements for linking up start-stop printers to channels of multiplex installations has already been referred to. Dr. Louis M. Potts also did extremely ingenious start-stop printer work, especially on the idea of the mechanical distributor and single receiving magnet or relay.

The Western Union and the British Post Office, being telegraph-operating and not manufacturing and development concerns, the Western Union engineers, like the British Post Office engineers, and the engineers of other administrations and operating companies, have had to discharge the important duty of testing and criticizing the machines designed by the various manufacturers and inventors, and it is largely from the conclusions arrived at and the requirements and conditions laid down by the telegraph-operating organizations that the manufacturers and inventors have been guided to commercial success.

I mention this because there is often uninformed criticism of the British Post Office on account of the Post Office engineers not having produced any of these printing-telegraph machines. They have not had time, and it would have been quite outside of their duties to have done so. The modern world is highly specialized, and the production and the operation of machinery are two entirely separate functions. Criticism and

valuable practical advice can come very properly from the operating administrations, but the work of development of machinery has to be left to the manufacturing concerns that specialize in that class of work.

German engineers, instead of accepting the conclusions of England, France and America in favour of mechanical operation, have employed automatic and electrical principles with success, and Messrs. Siemens and Halske of Berlin have produced a very interesting machine which they call the "Pendeltelegraph," printing on a tape at a speed of 40 words a minute. They have also developed another start-stop printer based on the Siemens automatic system, with a speed for manual operation of 60 to 70 words a minute, and, for automatic tape transmission, of 80 words a minute. It depends on many electrical contacts, brushes and condensers, devices that are not regarded favourably in the light of English and American experience, but it is stated to work well. Those who are interested will find an illustrated account of it in the *Elektrotechnische Zeitschrift* for 24th July, 1924, by F. Lüschen, entitled "Die Technik der Telegraphie und Telephonie im Weitverkehr." It is very instructive to compare the illustrations of this German machine with those of the Morkrum Company, Kleinschmidt, and Creed, all of which are mechanical. The same article gives an interesting diagram showing the remarkable network of Siemens' automatic printing-telegraph circuits linking up all the leading cities of Germany and Central Europe, and extending to London, Rome, Budapest, Vienna, Warsaw, Riga, Moscow and Kristiania and other Norwegian cities. This extension is due to German influence, and not to any superiority of automatic systems compared with multiplex; and if the forecast in this paper of the future of telegraphy is correct, then the whole of this automatic network will in due course find its way to the scrap-heap, because the multiplex is necessary for splitting up wires into a number of separate channels. Tone-selective methods are a practical alternative under certain conditions; but automatic systems are hopeless for the new telegraphy. Although multiplex are undoubtedly superior to automatic systems, yet even multiplex systems will be much modified by the requirements of the new telegraphy.

More recently others have entered the market, including F. G. Creed. The Creed machine, like all these printers, is most ingenious. It is based on the well-known Creed automatic printer, and it is unique in being a typewheel-typebar machine. The typebars are only $\frac{3}{4}$ inch long, and very high speed is secured in this way. The five-unit alphabet is used, and Mr. Creed is to be congratulated on his conversion from the morse to the five-unit system.

The essentials for success are now known, and from what has just been said it will be seen that healthy competition is springing up, and it is all for the good of civilization that every possible way of carrying out the start-stop idea should be investigated and tried, in order that the best may survive. That is specially desirable because of the very great importance of the start-stop printer.

(3) *Technical features of start-stop printers.*—The first essential of a start-stop printer is that it must start and stop for each letter transmitted and printed. Prefixed to each letter signal is a starting signal, which upon arrival at the receiving station starts the printing mechanism, which makes one revolution, in the course of which the letter is printed, and the machine then stops ready for the next letter. This cycle is repeated for every letter transmitted. (For simplicity, I have disregarded the overlap, as this does not affect the argument.)

A little consideration will show that there must also be a stopping interval to give the machine time to come to rest and return to zero. Hence the start-stop printers, although they employ the five-unit alphabet, are really seven-unit systems. The morse uses eight units per letter. The start-stop printers have therefore a slight advantage over the morse key of $12\frac{1}{2}$ per cent so far as the telegraph line is concerned.

The only alternative to starting and stopping for each letter is for the sending mechanism at station A and the receiving mechanism at station B to run continuously. For simplicity let us consider the Hughes printing-telegraph, which runs in this way. At each end of the telegraph line there is a typewheel, and these two typewheels have to run synchronously, that is to say, the same letters on each typewheel must point to the 12 o'clock position at the same instant, and mechanism has to be provided for correcting any lapse from synchronism. It is only while signals are being transmitted over the line that the synchronism of the Hughes is maintained. When transmission stops the Hughes falls out of synchronism, and synchronism would have to be re-established for each new connection before messages could be transmitted. In any case, to keep a number of Hughes circuits all tuned to the same speed would not be easy with the present governing mechanism. Also, in the event of no one being present at the receiving station there would be no certainty that synchronism had been established. Hence a printing-telegraph depending on continuous rotation, and therefore on synchronism, could not be used in a printing-telegraph exchange. The start-stop principle is essential. In any case, for reasons already mentioned, the Hughes would be out of the question for such a purpose.

The start-stop printer comes to rest between each letter or during intervals between messages, and it can then be switched easily from one circuit to another. The only condition is that there shall be approximately a standard speed for all the teletypes or other start-stop printers. About the subject of speed more will be said presently. It is true that even the "start-stop" machines depend on synchronism, but only during the one revolution that prints a letter, and it is very easy to preserve synchronism for such a short period as $\frac{1}{8}$ second or even less, and in this fact lies one of the great advantages of the "start-stop" machines for exchange work.

The next point about which some explanation is desirable is the mechanical distributor and single recording magnet of the successful start-stop printers. The Hughes is a single-magnet printer, but it does not have a mechanical distributor. In the Hughes the chariot is an electrical transmitting distributor only, and sends

out at station A an electrical impulse at the right moment for printing correctly at station B, the typewheel at station B revolving in synchronism with the typewheel at station A. The typewheels are the distributors, and in the Hughes there is no mechanical distributor in any sense corresponding to the mechanical receiving distributor of the modern start-stop printers.

(4) *Electrical and mechanical distributors.*—The value of the mechanical receiving distributor will be best understood by considering an electrical distributor and a printer in schematic form as shown in Fig. 4.

The receiving line-relay is shown at 1; 2 is the electrical start-stop distributor, the brush arm 3 being kept from revolving by the pawl 4. When a starting signal arrives in relay 1, it closes the contact at 5, and local current then passes from the battery 6, through ring 7, position, and the pawl 4, catching the brush arm 3, stops the machine until another starting signal, followed by a letter-signal group, arrives.

In electric distributors the chief difficulty is the contact brushes, which wear badly and require frequent attention. In the case of multiplex distributors the traffic and the carrying capacity are very great and the cost of daily attention to the brushes is trifling compared with the results achieved; but in the case of the start-stop printers the position is far less favourable. Such machines are necessarily scattered over a considerable area, often miles apart, and it would consume too much time and wages to send a man daily to attend to the brushes. The maintenance attention should not exceed once a week and preferably once a fortnight, or even once a month. Compared with an electric distributor using brushes, the mechanical

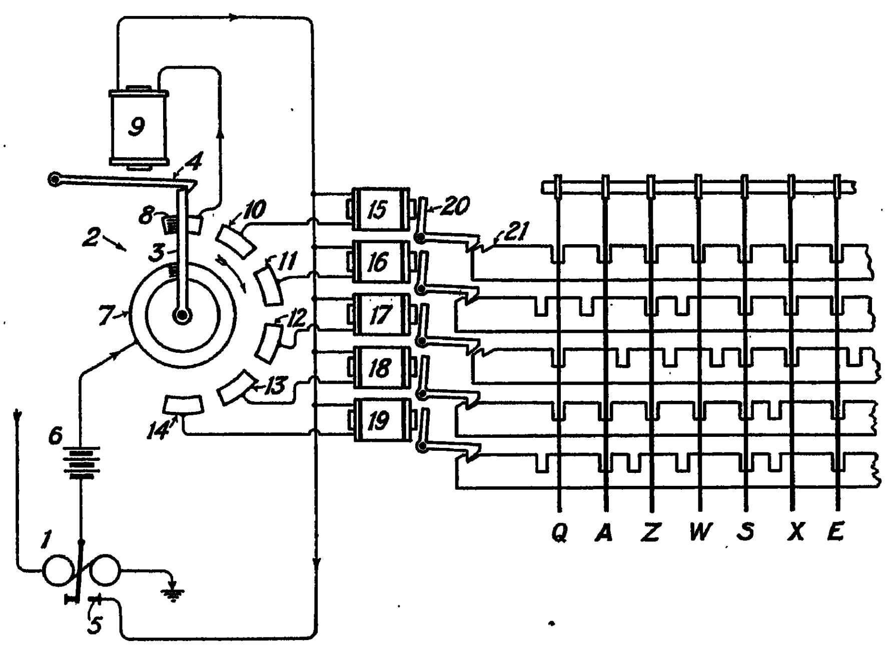


FIG. 4.—Diagram of principle of five-magnet printer and an electric distributor.

brush arm 3, starting contact 8, starting magnet 9, and back through contact 5 to the battery. The magnet 9 attracts the armature pawl 4, releasing the brush arm 3, which starts revolving to the right, the brushes making successive contact with the segments 10 to 14, which are connected to the five selecting magnets 15 to 19. Depending on whether the contact at 5 is open or closed by a line signal when the brush makes successive contact with the segments 10 to 14, impulses or no impulses will pass through one or more of the magnets 15 to 19, and one or more of the five armature pawls 20 will be attracted, and will release their corresponding selector plates 21. In this way a special permutation group of slots in the selector plates, corresponding to the letter signal transmitted, will be aligned and a latch, in this case corresponding to the letter S, will be selected and, by suitable mechanism, will print the letter S. The printing action also restores the selector plates to zero distributor is a great step forward. It does not require attention for months at a time and even then it only needs a drop of oil, which can be given by anybody. With the exception of one magnet to record the signals coming over the telegraph line, the receiving and printing mechanism of the modern start-stop printer becomes in this way entirely mechanical. Another important advantage of the mechanical distributor is the fact that, on lines not sufficiently long or difficult to require a relay, a start-stop printer equipped with a mechanical distributor can be worked by alternating current and without any direct current. An alternating-current motor to drive the machine is all that is necessary, in addition to the signal magnet to record the line signals. No local direct current is needed.

The principle of the mechanical receiving distributor is the same in all the successful start-stop printers so far produced, and it will be readily understood from

the schematic illustration of one form of mechanical distributor, in Fig. 5, and the following description :—

The signals arrive in the single magnet 1, which corresponds to a morse sounder. The first signal is the starting impulse and causes the magnet to attract its armature 2. This trips the pawl 3, and also by the link 4 it trips pawl 5. This throws in a clutch 6, which couples the constantly rotating power shaft 7 with the start-stop shaft 8. This carries the cam 9, and by means of five-to-one gearing it also operates cam 10. Cam 9 oscillates the lever 11 pivoted at 12. Lever 11 carries a rod 13, which is pushed by the rod 14 along in front of the five selector plates 21 (ends only shown, but they are the same as in Fig. 4), the rod 14 being moved by the cam 10. The rod 13 reciprocates regularly as shown by the arrow 15, under the control of the rod 11, which is kept oscillating by the cam 9. If, however, there is no operating or marking signal in the line, the magnet 1 will cease to attract its armature 2 and

contacts. These have proved wonderfully goo electric distributors, and run for months at a without attention. As a matter of fact, tun; contacts opened and closed by spirally arranged on a transmitting spindle are employed in the Morl teletype for the transmission of signals, and exper. shows that they run almost indefinitely without a tion. It will be seen, therefore, that there is a deal of variety possible in the design and manufac of start-stop printers. The mechanical distrib however, appears to be cheaper and simpler and i compact than electric contacts with five selec magnets, and the Morkrum teletypes, the Kleinsch: and the Creed start-stop machines all use the mecha: distributor.

The demand for high speed, at least 60 wor minute, has been a stumbling block. Typew machines like the Hughes and Baudot appear to r their commercial working limit at about 40 wor

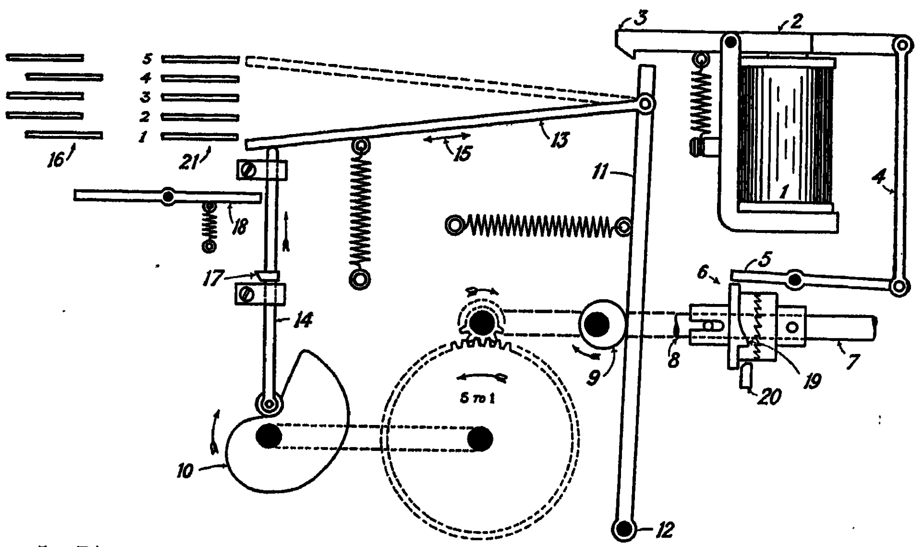


Fig. 5.—Diagram of principle of single-magnet start-stop printer with mechanical distributor.

the pawl 3 will catch and retain the rod 11, thus preventing the rod 13 from striking the selector plate opposite which it is passing at the time of no signal. Assuming that there is no signal operating the magnet 1 when the rod 13 is opposite selector plate 1, and that there is a signal when the rod is opposite selector plates 2 and 3, no signal when the rod is opposite plate 4 and a signal when opposite 5; then the selector plates will be pushed into the particular permutation shown at 16. Immediately afterwards, a tooth 17 on the rod 14 strikes the end of the lever 18, causing it to trip the printing mechanism into action, and a letter corresponding to the permutation set up in the selector plates will be printed. The clutch 6 is disengaged automatically by the cam surface 19 striking the plate 20, and the released half of the clutch is then caught once more by the pawl 5, ready for the starting impulse of the next letter signal.

On the other hand there has been a sort of rivalry between the mechanical distributor and tungsten

minute. Beyond that speed the cost of maintena rises rapidly, and American experience indicates t for speeds much beyond 40 words a minute the type principle is the best. The typewheel machine, howev has the advantage of great simplicity of print mechanism, and in one or two cases good results being obtained at higher speeds. There is a sin typewheel instead of 26 typebars and parts, and th is a simple little ink-roller instead of the necessar complicated ink-ribbon feed with automatic rever The demand for speed, however, is insistent, and t Western Union, as the result of great experience, l decided definitely in favour of the typebar machi: The Morkrum model-15 teletype is one reply to t: demand. This machine has an extremely ingenic mechanical distributor and, having typebars, it wo well at 75 words a minute and has been tested up to 1 words a minute. These high speeds are quite pra ticable for tape-printing, but, in the case of page-printir time has to be allowed for the carriage to run back, a

at 75 or 80 words a minute the time of at least three letter signals must be allowed for the return of the carriage. This is not a serious drawback, but it is a deduction from the high speed in the case of a page-printer. The Kleinschmidt direct keyboard printer is another answer to this demand for a rapid typebar typewriter-keyboard start-stop printer.

(5) *Curved code-bars.*—In the Morkrum model-15 teletype there are two, amongst other, interesting features demanding notice, namely, the curved code-bars and the combined striker-bar and lifting-bar. These two devices effect a surprising simplification in a typebar printer. I devised these two features and patented them in Great Britain in September 1922 (British patent 206975), only to find, on writing to the Morkrum Company, that they had hit upon the same ideas independently. We afterwards found that a French inventor named Eglin had patented a printer employing the curved code-bar idea in December 1912. He did not use the combined striker-bar and lifting-bar, and his selecting mechanism is rather complicated and apparently not very practical, and his printer is not provided with a distributor. It is for multiplex working with five selecting magnets, and it is not a start-stop printer like the machines referred to in this paper.

At B five magnets of the electrical distributor plan are shown controlling the code-bars, but the principle of the mechanical receiving distributor with a single magnet is readily applicable in the case of the curved code-bars, and it has been applied by the Morkrum Company in their model-15 teletype in a highly ingenious manner.

I have described this curved code-bar machine at some length because of the remarkable simplification obtained by the arrangement shown at A together with the semicircular code-bars shown at B. The importance of this simplification lies in the necessity for high speed, at least 60 words a minute, for start-stop printers. For such speeds typebar printers appear to be best; but typebar printers, owing to their complexity, have hitherto been very costly. The simplification resulting from the devices described above is therefore a distinct step forward, and in this respect there does not seem to be room for further improvement. The ink-ribbon mechanism of typebar printers is their one remaining drawback. It is more complicated than is desirable, and compares unfavourably in this respect with the simple ink-roller of the typewheel machines.

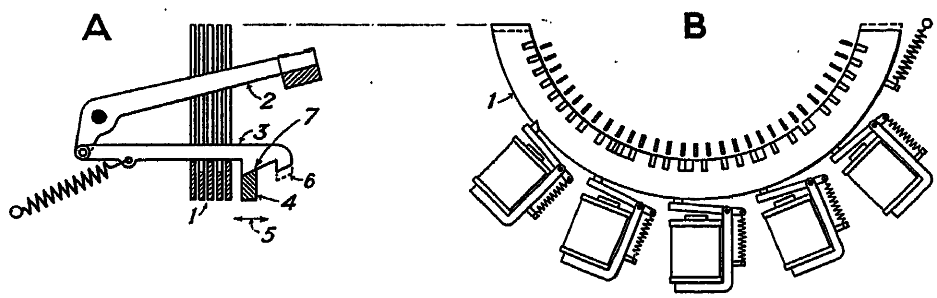


FIG. 6.—Diagram of curved code-bar printer.

In Fig. 6, A and B are the second and third diagrams in my British patent 206975. The Morkrum Company's solution of the problem is substantially the same. In A the curved code-bars are shown in section at 1; 2 is a typebar; 3 combines in one piece the selector latch, printing hook and connecting piece to the typebar, and 4 is the combined striker-bar and lifting-bar. At the right moment this bar moves forward and back as shown by the double arrow 5. When moving to the right it no longer supports the latches 3, which then rest on the curved code-bars. It is understood that there are 27 of these latches, corresponding to the 27 typebars. For any given permutation of the curved selector plates shown at B only one latch 3 will be selected and will be free to fall into the aligned group of slots, and the hook 6 will then engage with the striker-bar 4, and further motion of the striker-bar to the right will cause the typebar to rise and print. When the bar 4 moves to the left, the wedge portion at 7 lifts all the latches off the code-bars, which are then free to be set into a new permutation by the next signal transmitted over the line.

On the other hand, I am informed by the Western Union that as the result of 15 years' experience they found ink-rolls a source of great trouble and worry. They have found ink-ribbons far less troublesome and also cheaper than ink-rolls. This appears to be another case in which the complexity of the "Rolls-Royce" is preferable to the simplicity of the wheelbarrow.

(6) *Standard speed and tape- or page-printing.*—I have now completed the story of the new telegraphy and its machinery, and there remain only a few final words about one or two points that will cause difficulties if agreement is not reached in regard to them. They correspond in a curious way to the old problem of the standard railway gauge, which still gives the world some trouble.

The first and most important point is the question of a standard speed. Clearly the start-stop printers must run at approximately the same speed everywhere if there is going to be free intercommunication as on the telephone. In the case of the telephone this question of speed does not arise, because the speed is determined by the human voice, and we all talk at about the same speed (100 to 200 words a minute). In the case of printing-telegraphs the allowable speed variation

is small. Fortunately, so far as the machinery is concerned, this requirement is easily fulfilled by suitable governing mechanism, and tuning forks and the stroboscopic effect enable speeds everywhere to be regulated with great accuracy in less than a minute. The difficulty arises from other considerations.

The lower the speed the greater is the margin of security on the telegraph line; but the higher the speed the more words can be telegraphed within the time limit. The lower the speed the greater is the durability of the apparatus and the lower the maintenance cost, and the higher the speed the lower are the capital cost and the maintenance cost of the wire plant in proportion to the work done. The lower the speed the greater is the accuracy on the part of the human transmitter of messages; but the higher the speed the more business can be done and the more information and instructions can be transmitted within a given time. For circuits superposed on telephone lines, low speeds, say 40 words a minute, are desirable, while on ordinary telegraph lines higher speeds, say 60 words a minute, have advantages.

As start-stop printers or teletypes will have to be linked up with channels of the multiplex, the speed of the teletypes will be controlled by the speed of the multiplex, a matter quite easily arranged. Certainly it would not be practicable to alter the speed of big multiplex installations and networks, and quite impossible to give different speeds on different channels of the multiplex. Also the speeds of various multiplex installations differ in accordance with the line conditions. Certain fixed speeds for the multiplex are necessary, and a convenient solution of the intercommunication problem seems to be speed-change gears on the teletypes. The question does not arise in the case of carrier-current or tone-selective channels, except that the start-stop printer speeds between two correspondents must be the same.

There is still another question. What is the best working speed for a typist? There is complete disagreement everywhere on that point, and the rate advocated ranges from 40 to 80 words a minute. Apparently 60 words a minute may be accepted as the happy mean; but on long and difficult telegraph lines the speed of 40 words a minute gives a wider and safer margin for working. Evidently start-stop printers will have to be provided with three-speed or even four-speed gears like a motor-car, say 40, 60 and 80 words a minute. Two subscribers, on being connected at 40 words a minute, could agree on increased speed and gear up accordingly by moving a lever on each teletype. Even speed gears would necessitate agreement about the three or four speeds to be provided. These would have to be standard; but it would be much easier to agree on three or four speeds than on one. The question will have to be decided largely by experience, and fortunately in America there is a splendid field for experimental settlement of the problem. Later on, so far as Europe is concerned, there will have to be international agreement about start-stop printer speeds, and such agreement will have to include all leading nations because, in the course of time, teletype exchange and multiplex working will certainly extend through ocean cables and possibly by wireless across the great oceans.

The second and only other serious controversial point in connection with the new telegraphy is the question of tape- or page-printing. Tape-printing is considerably simpler than page-printing. It is therefore cheaper and the maintenance cost is lower. Also, for the distribution of market prices, weather reports and news to farmers and other private subscribers, tape-printing would appear to be the best arrangement. Using pre-gummed tape like postage stamps, the printed tape can be readily attached to sheets of paper. In the case of the Western Union Telegraph Co., after having about 2 000 page-printers in use all over the United States for the past 8 or 9 years, the company has decided to change over to tape-printing, and has already ordered over 800 tape-printers to replace page-printers. In this case, however, there are special reasons in favour of tape-printing, which do not apply in the case of Government administrations. There is sharp competition between the Western Union and the Postal Telegraph companies, and the Western Union prefers not to send out messages with visible corrections. Consequently, messages containing errors have to be retransmitted. This occasions loss of time and labour, which is avoided with tape-printing, as errors in tape can be cut out so as not to show in the finished message. There is also a considerable percentage loss of time in transmitting the signals to run the typewriter carriage back and turn up to a new line, and at the end of messages time must be given to the printer attendant to turn up to a new message form for printing the next telegram. In the case of news messages, on the other hand, page-printing has great advantages, because it saves time and labour, and it is doubtful if large firms with much telegraph traffic would accept tape-printing on their teletypes. They are accustomed to typewriters and they will demand typewriter service. That is to say, they will probably demand page-printing.

It is clear that there will be trouble if one subscriber has a tape-teletype and another a page-teletype. As it happens, a message containing page-printing signals will print all right on a tape-printer, but a message transmitted for a tape-printer without page signals will not print on a page-printer. A tape-printer typist could send the page-printing signals even on a tape-printer keyboard, but the situation is not as clear as could be desired. Of course as long as the Western Union and the Bell Telephone Co. confine themselves to their present plan of selling telegraph typewriter service only to business firms for use on their own private wires within their own organizations, the problem of tape- or page-printing will not arise. Each firm can choose tape- or page-printing; but when the inevitable linking up of such private-wire systems through a teletype exchange takes place, the tape- or page-printing problem will require consideration. One point to be borne in mind is that when start-stop printers are being used in great numbers, prices will come down, and it will then be practicable for firms to have several tape-printers and several page-printers, thus giving the option of either tape- or page-printing. For certain

classes of work page-printing is impossible. Fig. 3 is an illustration of what tape-printing can do and what page-printing cannot do. There is certainly much to be said for tape-printing in connection with the new telegraphy, but, on the other hand, page-printing saves time and labour when there is much traffic and it gives nicer-looking results.

(7) *A universal printer*.—Another point for consideration is whether it is not possible to have a universal printer available for all telegraph service. This, I understand, is the idea at the back of the mind of the Western Union, and there is much to be said in its favour. It certainly would be desirable to have a universal printer that would do for multiplex circuits, for start-stop circuits and also for stock-ticker service; and I, and no doubt others, have had our thoughts directed to this ideal for a long time past. Such a printer would be the real Ford car of printing telegraphy. A printer absolutely identical for all services is evidently impossible, but the modifications required for each class of work are not serious. The five-unit alphabet being used, all the essential parts of the machine would be the same for each service. This would allow of production in quantity, with corresponding reduction in cost and corresponding extension of the field of telegraph service. The answer of the Morkrum Company to this requirement is the new Morkrum model-15 teletype which will work up to 80 words a minute. It is tape-printing or page-printing as desired. It is a start-stop printer with a direct-transmitting typewriter keyboard, or it can be used with a keyboard perforator and automatic tape transmission. By substituting five selecting magnets it can be used on multiplex circuits. Apparently there is nothing to prevent any of the start-stop machines being so constructed as to be available with suitable modifications for these various services, and it will be a question for time and the telegraph administrations to determine which is the best.

Hitherto stock and news service has been confined to city limits on account of the step-by-step principle of signalling employed. The use of a modern start-stop printer for the distribution of news and market prices will sweep away the city limitations of stock-ticker service, and distribution will become nation-wide. The five-unit alphabet being used, there will be no bar to universal ticker service, including distribution to distant centres over channels of the multiplex. Prices are already being broadcast by wireless; but the arrangement is unsatisfactory. Only a few leading prices can be given, because to listen to a whole stock-list for the day by wireless would be unendurable. Also, broadcasting suffers from all the disadvantages of the telephone. It is a voice and nothing more. There is no record and there must be fixed times for listening, and there is the risk of error of the telephone plus the risk of error from atmospherics or static. The printing-telegraph for news is the only way.

In America, for instance, there is already a very fine ticker service (and so there is also in this country); but with the new machinery it will certainly develop to a marvellous extent, covering the whole of the United States and Canada, and serving not only stockbrokers and produce dealers but also farmers and private homes. Every well-to-do family will have its ticker service superposed on its telephone line for news and its radio set for amusement. The family will turn on the music and read the news.

(8) *Prices*.—At the back of all the wonderful possibilities outlined in this paper is the question of cost. Will it pay? That depends on the value of the service rendered. Printing-telegraphs have already proved extremely valuable to telegraph administrations, and there is acknowledgment of that fact in the annual report of the Western Union Telegraph Co. for the year 1920. In that report it was stated that, since 1915, multiplex printing-telegraph apparatus had been installed costing approximately $2\frac{1}{2}$ million dollars, saving the expenditure of $16 585 000 on wire plant, which otherwise would have been required. Nothing was said in the report about the labour-saving, which is known to be substantial; and during the four years that have passed since that report was issued there must have been still further expenditure and resulting economies both on lines and labour, bringing the total saving to the Western Union up to somewhere about 4 million pounds sterling. There is no doubt that printing-telegraphy is very profitable to the telegraph administrations. It is also very profitable to newspapers and news-distributing organizations, and the stock-ticker service manages to pay its way in most countries. This paper also will have been written in vain if the start-stop printers do not render profitable service on a large scale; but there is a law of diminishing returns in such cases, and the margin of cultivation may be taken as the employment of the start-stop ticker in the home. For stock and produce brokers, merchants and farmers, the teletype will undoubtedly render commercially valuable service for which it will be worth paying a substantial price; but in the home the ticker, like radio apparatus, must be regarded as a luxury, and the extent of this particular market will depend on low prices and cheap maintenance. These are also important considerations in the more profitable markets already referred to. In short, everything depends on the price.

Reference has already been made to the unprofitable years of development work and the heavy expenditure incurred in producing these simple-looking little machines, the start-stop printers. Naturally the manufacturers have to get their money back with a profit or go out of business, and the present selling price of these machines is therefore about £90 to £180, depending on the amount of apparatus and kind of service required. Not only has the production been expensive, but the cost of selling is high. The "education of the market" takes much time and money. However, with the increase in the numbers sold, the cost of selling as well as the cost of making will fall, and when the stage of mass production by tens of thousands is reached and orders run into thousands at a time, the prices will fall probably to about twice the cost of a typewriter of the better class. If the total sales ultimately go into the millions like typewriters, it is possible that the prices will come down to the typewriter level, and they will then find their

way into the more prosperous homes, just as the portable typewriters are doing. Mr. G. M. Yorke, Vice-President in Charge of Engineering, Western Union Telegraph Company, New York, writing to me on the 1st May, 1924, said:—

"We agree with you that one difficulty about the printing-telegraph business is the cost of the machines. We hope to get American manufacturers on a Ford-car basis within the next 5 or 6 years. However, on the whole, our regrets in connection with our printing-telegraph developments are small."

In conclusion, it may be of interest to add that official steps are already being taken to investigate the new telegraphy thoroughly under experimental conditions, and, if the results are promising, it is probable that some form of practical trial will be made. Fortunately, the new telegraphy lends itself readily to experimental laboratory trials with a couple of small 10-line switchboards and a dozen start-stop printers, and I anticipate that, as the result of this paper, experiments of this kind will before long be instituted by all the leading telegraph administrations.

Discussion before The Institution, 18 December, 1924.

Colonel T. F. Purves: Although I am not at liberty to speak very freely on this subject, I should not like it to be thought that the Post Office does not feel the keenest interest in the proposals put forward by the author. I might say, indeed, that any suggestion from him on a subject of this sort would always be treated with the greatest respect, and, as he knows, steps are already being taken in a practical way with a view to giving his proposed method of communication a practical trial under the most favourable conditions that we are likely to find in this country. In that way I hope that before very long we shall have a certain amount of actual evidence to show to what extent the British public is prepared to support the proposal to provide a printing-telegraph switching system for personal use by subscribers. I rather emphasize the words "British public" from a point of view that will appeal to those who have had occasion to study the viewpoints of different nations, or to compare their various degrees of responsiveness to publicity and advertisement, either private or governmental. I quite agree with the author that the great weakness of the telegraphs is lack of what he calls terminal facilities. On the engineering side his proposals involve many problems that will require much study in their economic realization, but in themselves they present no serious difficulties. The author describes enthusiastically and quite legitimately the large numbers of channels of communication that can now be obtained from a single telegraph or telephone line by modern methods of multiplexing or superposition. These methods have gone very far and will no doubt go further still in practice, but I should like to mention that another factor is also at work inasmuch as the scientific study of line conditions and construction, and the application of repeaters, is reducing the cost of providing lines in great numbers between important traffic centres. The annual costs associated with multiplex telegraph and telephone apparatus are fairly high, and the point at which it is economical to provide additional lines and use simple self-contained apparatus is a shifting one. There may be some reaction in favour of not demanding from the line all the effective signalling speed of which it is capable, especially in connection with switching systems which are apt to become so complex in themselves that the additional complexities of multiplexed channels are formidable. The author is quite entitled to claim, as he does, that the telegraph can transmit intelligence with a far smaller number of line impulses than the telephone, but I think that his arguments on pages 248 and 249—based on his Fig. 1—go rather too far. The telephone has to transmit over its line a frequency as high as 2 500 per second in order to be properly intelligible, and the equivalent telegraph speed of that line, at 7 impulses per letter, is 6 850 words per minute. It seems too good to be true! I think that the author is overlooking one thing which entirely alters the practical aspect of the comparison, and that is the respective efficiencies of the receiving apparatus—in one case a telegraph receiving apparatus, and in the other case the human ear. The power of the human ear to correct distortion and to transmit intelligible signals to the brain is nothing short of marvellous, whereas only a slight amount of distortion will completely upset a printing-telegraph receiver and convert its record into a mass of meaningless symbols. It is generally admitted that the telephone is not well adapted for the transmission of written messages and figures, but that disadvantage applies rather to its use by the public than to its use by practised experts who are accustomed to work together. It is generally a slow and painful business to dictate a phonogram, but I have listened to the transmission of news at a very rapid conversational speed between London and Paris on frequent occasions, practically without any hitches or any requests for repetition, and being taken down, of course, in shorthand at the other end. I have been, too, in the offices of busy stockbrokers who have been transacting important business over the telephone, and receiving figures and fractions at high speed, and the work has been going on with perfect facility and no sign of any strain. I feel that one must be fair to the telephone in this respect. I think also that the author is a little less than fair to the possibilities of broadcasting market news by wireless; and I would suggest that it is not very safe policy for a printing-telegraph engineer to make light of such possibilities. I welcome the paper as a notable contribution towards the very desirable end of revivifying the telegraph service, which, both in this country and elsewhere, has been in danger of sinking into quite undeserved disrepute. As the author remarks, the need for a simple printing instrument for the use of renters of private wires between their offices and public telegraph offices has been felt for many years and is now at last met. The same instrument is excellently suited for a direct

intercommunication system, if such a system is wanted by the public. The "start-stop" feature, which has so many advantages, is perhaps not ideal for a switching system to be used outside of office hours. I question whether many people would care to transmit important confidential messages without having received an intimation that they had really been placed in communication with the office they required, and without any acknowledgment of receipt. I rather think that the fear of having got connected to a wrong number, and of giving some useful information to a competing firm, would be a decided deterrent to the adoption of such a system. I am not impressed either with the suitability of the printing-telegraph for sending and receiving service switching instructions. In spite of the attractions of an entirely separate telegraph switching system with multiplexed lines, I think it would be well not to rule out the idea of combining it with the general telephone system, which already provides a great and ever-growing network of switching channels running everywhere. The new system of voice-frequency telegraphy makes it possible for the telegraph to be worked on any circuit that will carry a telephone conversation—with all its equipment of manual or automatic switchboards, transformers, loading coils and speech relays—and the facility of switching at will from the telephone instrument to the printing-telegraph, and vice versa, must prove a great asset. The telegraph instrument must, of course, be suitably designed and equipped from the signalling standpoint. Its line current must be kept very low in order to avoid interference with the telephone system, but that is a condition which must apply in any event, as telephone and telegraph conductors are now inextricably united in the new underground cable system of the country. I might remark also that the author's financial calculations as to remunerative rates, etc., refer to conditions which seem to approach a good deal closer to the ideal, in the matter of steady and continuously sustained traffic, than is ever likely to be experienced. As regards the automatic switching of telegraph circuits, it may interest the author to know that a good many years ago the question of converting the London intercommunication system to automatic switching was under consideration, and a system was designed (on paper) which would have met all the conditions. It was not proceeded with because it was then becoming obvious that the competition of the telephone would, in a comparatively short term of years, do away with the need for maintaining a telegraph switching system for the offices of the London area.

Mr. J. Newlands: The author says that the telegraphs as we know them in this country are slow, costly and inefficient. From the commencement (in about 1846) the telegraphs grew like a tree and the different branches had to be interconnected. It is still much too like a tree; there are far too many different transmitting points, and that is the real cause of this slowness and costliness. In the early days different kinds of apparatus were taken over from different companies, many of which have entirely disappeared. The single-needle system has practically gone out of the Post Office service, as also have the acoustic needle, the A.B.C. and Bright's bell. We have here a paper the author of which tells us candidly that he thinks the day has come when the sounder also ought to go—that it has served its day and generation, and has become more or less obsolete. I am inclined to agree with him, but we must remember that while the sounder is very cheap and easily produced in large numbers, the present cost of the teletype is almost prohibitive. I quite agree with the author that there are too many circuits, and that the terminal facilities are at fault. What is the reason? The apparatus is far too slow; the operators were too slow; many of them are still too slow. I tried for many years to improve the rate of working by what is known as the "average" system; but my efforts fade into insignificance compared with the author's sweeping recommendation to "scrap the lot." As the telegraph business grew, the number of offices on a circuit had to be reduced to 3, 4 or 5. There are very few circuits that I can recall which have more than 5. Now, if the teletype is so constructed that not 5 but twice or three times 5 offices doing a moderate amount of business can be put on a telegraph circuit, then its increased rate of working will enable a great many of the existing circuits to be grouped on to one teletype, and in that way it will effect economies at transmitting offices. I think that is possible. The telegraph distribution system of this country will have to be totally revised if the teletype is to have a really good chance. If the sounder is to go, then I would suggest that the transmitting offices should be roughly something as follows: London (with a wide area), Bristol, Norwich, Birmingham, Nottingham, Sheffield, Leeds, Manchester, Liverpool, Glasgow, Edinburgh, Aberdeen, Belfast, Dublin and Cork; that these larger places should be freely interconnected, and that they should reach all the area around them. This would, I believe, greatly reduce the number of transmissions to and from rural localities, probably to an average of two per message. The author, in endeavouring to show how people sitting in their offices could be connected all over the world, refers to the question of a "bottle-neck" at the cable ends. Now, one of my former operators, Mr. J. B. Heggerty, suggested a reversion to the old Umschalter switch such as is now used in Belgium. He proposed a system of joining through each telegraph office "direct" to any other office it required, each in turn. That is perhaps suitable in a country such as Belgium, where Antwerp and Brussels are within easy reach of the whole system, but Mr. Heggerty's scheme was turned down for the reason that it is impossible to be continuously altering the length of a circuit. The author proposes to switch through direct up to 5 000 miles. The faults which are inherent in our telegraph system would, I think, condemn such a scheme as that; there would be "bottle-necks" all over the country. With regard to a teletype exchange system for London, I do not think there is a real case for that at all. The author admits that the telephone is much better suited for such a populous city, where there is not a great deal of telegraph communication except between the head office and a business firm's works. On the other hand, I think that if there is an

effective demand in the country for a teletype exchange similar to the telephone exchange, it ought to be attached, not to the telephone system, but to the chief or central telegraph office, which, in connection with its phonogram room, should have certain wires put apart. Let me take for illustration the most central town in England. If there is an effective demand on the part of business men or stockbrokers or banks for a teletype exchange from London to Birmingham, I think the department should put one good experimental wire at the disposal of the Central Telegraph Office and see what it can obtain in the way of business. I see great possibilities in the way of the simplification of telegraphy by the adoption of the teletype for speeding up the telegraphs. I see the prospect of great economies on the part of the administration, especially if the cost of the teletype can be lowered, and, if the teletype apparatus can be made in bulk in this country and can be placed at the command of the Post Office, I think that it will make very rapid progress indeed.

Mr. E. H. Shaughnessy: On page 254 the author says: "The circuit facilities will be still greater when half a dozen wireless beams work across the Atlantic each at 300 words a minute." I think that this is even more than wireless engineers will prophesy with any degree of confidence; but on the next page I read that: "Even if this were possible, there are the inaccuracy of wireless, interference troubles and atmospherics, and there is no way of answering back." So that although he is looking forward to wireless to help him, at the same time he says that wireless is no good. When discussing costs, the author speaks of the rapidity with which this scheme will enable telegraphy to be carried on, and on page 260 he says: "A great advantage that the telegraph possesses over the telephone is that a telegraph message can be stored up at any point where there may be a 'bottle-neck,' until its turn comes for transmission." This indicates that a fault of the present telegraph delay owing to bottle-necks is even turned into an advantage in this method. The price of the teletype, or any form of start-stop printer, viz. £90 to £180 as given by the author, must undoubtedly be reduced if the telegraph is to compete with the telephone. It will be a very serious position if a million subscribers are obtained, in each of whose offices an instrument costing £100 will have to be installed. First of all this would involve a capital expenditure of £100 000 000 for instruments alone, and I think that is the sort of development visualized by the author in 25 years' time.

Mr. J. E. Kingsbury: Reading the paper from the telephone point of view I have some doubt whether it will be possible to introduce his method in the way the author suggests. For the purpose of analogy I have compared the conditions with railway traffic, of which there are two kinds, passenger and goods. The passenger traffic we may consider as being of the first importance, and for the purposes of analogy we may call speech the passenger traffic and the written word the goods traffic. Now terminal facilities for goods traffic are usually regarded as a very expensive item, and only to be taken advantage of by those who have a great quantity of goods to despatch. Terminal facilities from the point of view of the telegraph were, we must remember, suggested even earlier than the author records in his paper. Simply as a matter of history I should like to remind him that the first exchange system was that patented by Dumont in 1851. It was there suggested that the telegraph line should be taken into the house or the office of the sender and the receiver. Now if the most is to be made of long-distance facilities the goods must be collected in detail, forwarded in bulk and distributed in detail. In a sense that is what is done by the telegraph of to-day. The author suggests that better results can be obtained only by forwarding direct from the sender to the receiver. To my mind that is all a question of cost and convenience. In the case of a line capable of conveying the number of vibrations shown in Fig. 1 (which are adapted to the machines at either end as at present used, but depend for the economic use of the line telegraphically on the multiplication of a number of machines utilized by different people), economy is dependent upon the simultaneous requirements of a number of people to use that line—and in practice, of course, the requirements will not be simultaneous. The collection of goods at a central depot, from whence they would be forwarded in bulk to some other distributing centre, would enable more traffic to be obtained from the line itself than would the general provision of terminal facilities. On the other hand, there can be no question of the great advantage to certain users of direct telegraphic communication such as the author proposes, but I would suggest that the system should be tried in the first instance in an independent teletype exchange. I think that if the teletype printer were added to the existing telephone system, the telephone subscriber would strongly object to find that his line, which was adapted for passenger service, was being monopolized for goods to the detriment of his passenger service. Again, the cost of the teletype appears to be so high as to justify the further increase necessary to give it a separate line. Therefore I think that the author should amend his estimates by making provision for a separate teletype exchange in order to give the system a fair trial.

Mr. T. B. Johnson: I agree with the author that there is a field for the extension of the telegraph in work for which it is more suitable than the telephone; and I say that in spite of the fact that I am an enthusiastic advocate of the development of telephony, and especially automatic telephony. The crux of the question is to what extent the business man really wants a written record. It is exceedingly creditable that transactions of such importance as are carried on at every moment of the day, depending entirely on the word of the men at the ends of the line, are honoured and carried out, but still there is some need for a written record. Whether the start-stop printers would satisfy the requirements I am unable to say, but if they will—and the author states that they can be transferred from a short to a long line—then I believe that there is a field for them. Broadly speaking, material is cheap and labour is dear; and if we can save labour every day the cost of these machines, which will inevitably fall considerably as their use

extends, will not be a really serious bar. At the present time there is far too much writing down of telegrams in different places. Take Leeds and Bradford, for instance, each of which cities has some smaller telegraph offices connected with it. A telegram from a place near Bradford has to be written down in Bradford; it has to be transmitted in turn to Leeds and to the office near Leeds. Teletype exchanges at these two cities would save a good deal of transmission, and each transmission in addition to the cost also involves an additional risk of error. The author, in his estimates, has not taken sufficient account of the cost of labour at the switching centres. In practice it would be found that the cost of switching of telegrams would be much more than he anticipated, and telephone engineers will agree with me that the cost of switching, no matter what attemps are made to cheapen it, is always appreciable. It would, however, be much less than the present cost of writing down and re-transmitting. I do not agree with the author that farmers will take much advantage of the teletype machines; the English farmer is much too conservative. It is very difficult to persuade him to take a party-line telephone; and when some time ago the Post Office telephone authorities distributed weather forecasts from their rural exchanges, it was found that so few people wanted them that they have been practically discontinued. Another important point is that these machines must be so constructed as to require no adjustment at the subscriber's office. Although I do not think that the sounder will become obsolete, its use will continue to diminish and the tendency which there has been of late years to make the telegraphist either a typist or a mechanic will continue at an accelerated rate. The type printer is bound to supersede the sounder for the greater part. It is rather surprising—as showing the conservatism of the ordinary English user—to find how little the facilities which the telephone administration does give in other directions are made use of. For instance, very few people take advantage of the system whereby a telegram may be addressed to a person's telephone number, thus enabling the message to be telephoned from the main telegraph office and saving the time occupied in delivery.

Mr. A. E. Thompson: In view of the subtlety of the distinction which the author has drawn between the telegraph and the telephone, the fact that the ordinary business man with the telephone at his elbow uses it for much traffic that could be handled more economically by the telegraph is not surprising. Undoubtedly the telegraph has suffered by the want of a satisfactory connecting link between the user and the administration. Instead of being regarded as a normal means of communication, it is only used in extreme necessity and it has thus become associated not with the active side of life but rather with catastrophe, sickness and death. Telegraphy has thus itself become enfeebled. In comparing the relative transmission efficiencies of the telegraph and the telephone, the author states that when the word "Paris" is spoken, 365 waves are transmitted, as against 21 waves when the same word is telegraphed. This assumes that only the fundamental frequency is transmitted in the case of the telegraph, whereas the square-shaped signals necessary for machine speeds are built up from a number of harmonics. The importance of these harmonics is clearly illustrated by the "composite" system of superimposing. In this system the telegraph signals have to pass through a filter network having a fairly sharp cut-off at about 80 periods per second. It is not possible, however, to telegraph at this speed, and in practice the maximum speed obtainable is between 20 and 25 periods, which is sufficiently low to permit the third harmonic to pass freely through the filter. A more direct, and more striking, illustration of the admitted economy of the telegraph, from the line standpoint, is afforded by the Western Electric Co.'s "voice frequency" telegraph system. Take, for example, a 4-wire telephone circuit providing one speech channel in each direction. If the telephone is given up, and if the same line plant is then equipped at its terminals with the Western Electric system, from 10 to 12 independent telegraph channels can be obtained. Each of these channels may, in turn, be equipped with multiplex-quadruplex printing telegraph apparatus, giving a total of 40 to 48 message-channels, or a traffic-carrying capacity of approximately 1 200 to 1 400 words per minute. If only two wires are available the traffic-carrying capacity is reduced to 600 or 700 words per minute, but this is still considerably more than the telephone can handle. In the section dealing with teletype exchanges, the author states that the Bell Telephone Co. is starting to sell telegraph typewriter service to business men in Chicago, on similar lines to the Western Union. This may perhaps give the impression that leased wire telegraph service is a new practice in the United States, whereas the Bell Telephone Co. has, of course, been leasing printing telegraph facilities for a number of years past. The only new feature is that the Illinois Bell Telephone Co. of Chicago is now offering the teletype apparatus for use on its lines. With regard to the telegraphy of the future, a matter which requires some consideration if the telegraphs are to be linked up on an extensive scale is the establishment of a standard 5-unit code. At present three or four different arrangements of this code are in use in Europe, but investigation will probably show that the code used by the "teletype," the Murray multiplex, and the American multiplex and start-stop systems, is the most satisfactory from every point of view. When the administrations adopt a common 5-unit code, then with such developments as the simple typewriter-telegraph, the "composite" system, and the "voice frequency" telegraph system, the author's vision of the new telegraphy should soon be realized. As Mr. John Lee, the Controller of the Central Telegraph Office, so aptly states in his book "Telegraph Practice," "The old mystery of the telegraph is breaking down; the public is no longer to be separated from the organism by the fortification of a counter. The telegraph system is no longer to find its bounds and limits in telegraph offices. It will penetrate into industry itself; it will link up all manner of industries with each other and with whatever centralizing bureau shall yet be evolved."

Major F. H. Masters: A previous speaker has stated that the facilities available for telephone subscribers are not made use of, and complained that it was difficult for the Post Office to advertise those facilities. A body known as the Telephone Development Association has recently been formed, and it would appear that it should be part of their duty to advertise existing facilities. I should like to suggest to the author that some of the advantages which he puts forward for the teletype system could be obtained rather more simply by using the telephone in connection with the telegraph.

Mr. W. J. Thorrowgood: A point of view which does not appear to have entered into the author's calculations concerns the user of this apparatus. It has been said that the user of a telephone does not always know how to manipulate a receiver after he has used it. If he is to use the teletype machine to any extent, I venture to say that the cost to him of learning how to use it will be very considerable. A man operating a typewriter at 40 words a minute must give his whole attention to the work; whereas if he speaks over the telephone he is thinking of what he is saying, and he conveys a good deal by the way in which he says it. The teletype writer to an ordinary user is not so comfortable to use as a telephone, and a telephone lends itself so easily to business men that it seems to me that a teletype has no chance at all—certainly in view of the possible advances that can be made in 25 years, the period mentioned by the author. When calculating the number of words that can be sent by telegraph, or telephone, it must be considered that the unit of telephone communication is not letters, words, or messages, but a conversation, which may consist of several messages, certainly not less than two.

Mr. A. C. Brown: There is one thing which might very easily alter our conception of the whole subject, and that is the "Telephonograph." That, of course, is not a new proposition; it is quite possible now for telephone subscribers to have an instrument which will automatically start when a call is given from the exchange, and which will record the telephone message and deliver it up when it is wanted. I fancy that a considerable use of such apparatus would enable a great many of the difficulties of switching to be avoided, and might possibly considerably affect the number of telegraphs required.

Mr. J. S. Jones: The author appears to base his attack on the existing telegraph service in this country on two paragraphs which appeared in the *Daily News*. The first of these paragraphs, however, has no reference to the British telegraph service and the second is largely incorrect. The alleged system of telephoning express messages from one exchange to another has never existed and the subscriber at Norwood, far from having a new facility in being put through to the Central Telegraph Office, has in fact had that facility for 30 years. I do not think, judging from the evidence at the General Post Office, that the public is dissatisfied with the present telegraph service. The author thinks that there are too many circuits and I take it that he means that the Post Office does not take proper advantage of the devices which exist for superposing and multiplexing. Leaving reserve wires out of account, there are very few telegraph services in this country which require two or more wires, for the reason that multiplex working is in operation on all heavy routes. Presumably the author's view is that more could be done to cut down the number of physical circuits by forming channels by multiplexing, or by the tone-frequency method, and extending them by short-distance physical circuits—for example, by forming a number of such circuits between London and Birmingham and extending them to Nottingham, Manchester, etc. Such a method, however, has the great disadvantage of placing too many eggs in one basket. In any case, expedients of this kind could be applied to very few routes in this country. A system of transmitting centres as advocated by Mr. Newlands was in fact introduced in the British telegraph service nearly three years ago. It had some effect in reducing the number of re-transmissions of telegrams, but it could not reduce the number of re-transmissions per message by 2, as asserted by Mr. Newlands, for the reason that the average number of re-transmissions per message is actually 1·2. The author envisages the telegraph service too much as a business-man's service. It is used by all sorts of people, and the number of persons sending more than, say, three telegrams a day is comparatively small. A very few send large numbers of telegrams and the system of direct telegraphing proposed by the author would be quite unsuitable for them. The author proposes the establishment of a telegraph system practically on the same lines as the telephone service, but such a service would involve the provision of three or four times as many telegraph channels as exist at present. There is unquestionably a field for teletype exchanges, but it is highly improbable that the possibilities of development are as extensive as the author suggests.

Mr. G. F. Findley (*communicated*): It would appear that in order to obtain a true vision a forecast of the telephone development must be placed alongside this forecast of the new telegraphy. In view of recent achievements it is not necessary to consider the telephone development 25 years hence. I think that the development of telephony in the next 10 years will make the present system appear very crude. The improvement in the telephone service provided by the "no delay" conditions created within the London "toll" area, between the Liverpool area and the Manchester area, between the Glasgow area and the Edinburgh area, etc., and the advance in transmission efficiency, manufacture, laying and maintenance of telephone cables and, last but not least, the advance made in the telephone repeater, force me to anticipate a telephone development along the following lines:

(1) It will be possible at moderate charges for calls between all large cities to mature with a maximum delay of 10 minutes and for calls between towns within the vicinities of these large cities to enjoy the same standard of service. In fact, practically the whole of Britain should have a 10-minute service on terminal calls.

(2) The maximum delay on a call from Plymouth to Aberdeen (a through call) should not exceed 20 minutes.

(3) The telephone will become as vital as electric light and power, water, etc.

As the natural way to communicate with one another is to talk, I am unable, in view of my vision of the telephone development, to realize how the author's scheme can live. There will be no necessity to "teletype" when one can "teletalk" without delay and for a moderate charge. Where documentary confirmations are essential—and I am of the opinion that with the advance of telephone education these confirmations will be very few—the post will be sufficiently speedy. The author appears to have overlooked also the ease of correction by telephone as compared with teletype, especially simplex teletype, working. He says that, with the new telegraphy, telegraph instrument rooms will be deserted, as they will become switching centres and the stability of circuit conditions will be established. At present, it would appear that every circuit is worked under different conditions and that any scheme which embodies the word "economy" a sufficient number of times is given prominence and a trial. I think that one of the real planks of economy is efficient standardization and mass production, which will cheapen the article to the consumer. With simple apparatus such as the telephone and a straightforward issue, viz. "The required persons to talk," a delay of 60 seconds is experienced on long-distance calls, after the subscribers' telephonists have answered, before the required persons commence talking. I can see a considerable increase to this delay before "the required persons can type." Therefore in all the circumstances—the main being the development of the telephone—I cannot see the necessity to "teletype" when one can "teletalk" with efficiency and economy.

Mr. T. E. Herbert (*communicated*): The first two parts of the paper may be described as an extension of a paper * read before the Institution of Post Office Electrical Engineers at Manchester on the 3rd March, 1924. In general, the conclusion arrived at in the paper quoted is the same as the author's, viz. that the time has arrived when some form of automatic switching must be adopted. The telegraph ought to be the cheap, speedy and democratic method of conveying messages which cannot suffer the delay of the ordinary post. The cost of the telegraph plant is necessarily much less than that of the corresponding telephone plant required to convey a message over a moderate distance. If the plant or capital charges of telegraphs are compared with trunk-line capital charges, it will be found that the latter are much heavier. The net receipts from telegraphs are higher than for telephone trunk lines, and yet the former consistently register a loss and the latter a profit. The operating costs, including the cost of delivery of messages, are very high. By eliminating the re-transmission of messages, not only is the cost reduced but greater expedition is secured. It is, of course, a matter of opinion as to whether the business community can make use of a quick telegraph service, but it is certain that present-day business could not be conducted without our present means of rapid communication and transport, mechanical and electrical. It therefore seems reasonable to suppose that increased rapidity has a definite monetary value, and it scarcely seems idealistic to suppose that in time greater expedition in business arrangements will become, not a luxury, but a necessity. This greater rapidity will have to be paid for, but if the results are commensurate the extra cost of telegraphing letters as compared with the ordinary post will assume very minor proportions. The telephone trunk conversation is regarded as essential for personal communications and personal discussions of urgency, and from the enormous use made of trunk lines it is clear that this aid to business is fully appreciated. The interruptions by telephone-calls on relatively minor matters are, however, sometimes serious and would be avoided by the use of a telegram—the caller has not to obtain a telephone connection, nor is the called person interrupted in his occupation of the moment. The telegram is received and dealt with in the called person's office, and the consultation which may be necessary for the reply is effected in the least possible time, since all the data are available when the matter is to be decided. All this, however, postulates a service which is cheap and extremely rapid. Close and careful investigation is called for, and from the large number of papers on the subject of telegraphs now appearing in various technical publications, and from discussions by telegraph and telephone societies, I think it is certain that the problems can and will be solved—to this end the author has contributed a most valuable piece of constructive criticism. On page 247 he states that it is hopelessly idealistic to suppose that the telegraphs have value for short distances. It is by no means certain that the value of the written record and the avoidance of interruption to, and by, important executives has no recognized value. In the event of the main telephone exchange in a town or city being destroyed by fire, the telegraphs would serve to mitigate the disaster since there would be no difficulty whatever in providing a relatively large traffic-carrying system at short notice. The restoration of the exchange would necessarily occupy weeks or months, according to the size and nature of this damage. The "engaged" difficulty referred to on page 259 could be met in yet another way. The message might be received on a receiving perforator allied with a transmitter which would seize a waiting point for the line required and, when this was free, proceed to transmit the message. The point to be appreciated is that this machinery standing idle waiting to re-transmit the message saves human labour, and it is the cost of such labour which necessarily keeps up the cost of telegrams. I am disposed to think that special circuits for telegraphs, rather than the joint use of local subscribers' lines save for very small users, is the most probable development. The failure of the London intercommunication switch is not a valid argument against the suggestions now made. It depended on manual switching and on the skill of morse operators at small offices. Also, it seems possible that the area served by each office for delivering messages was too small for economical operation. The first step (p. 264) should, I think, be in the direction of providing an automatic switching system such that no manual re-transmission of messages should take place between telegraph offices. In conclusion, I am by no means in agreement with the author's suggestion that

* T. E. Herbert: "The Problem of the Telegraphs," *Telegraph and Telephone Journal*, 1924, vol. 10, p. 126.

telegraph clerks will disappear. It will be precisely as with automatic telephone exchanges where a large number of women are always necessary for special switching, accounts work, and many other duties. So with telegraphs, a large staff will always be required and if the volume of the work increases under the new conditions I think it more than probable that the functions of the staff may be changed but that great displacement will not occur.

Mr. Donald Murray (*in reply*): I am glad the Institution has given me so much liberty in the preparation of this paper, because I might have been asked, quite fairly, to make it more technical in tone and substance. In view, however, of the importance of attracting public attention to the idea of teletype exchanges, it would have been unfortunate if any restriction had been imposed on the popular journalistic method of presentation that I have adopted. Technical men would also have been justified in complaining of the length of the paper; but it has been well said by Sir Oliver Lodge that "effective exposition cannot be done crisply and compactly." For these and other reasons I expected a good deal of adverse criticism, and I have therefore been agreeably surprised at the very friendly tone of the discussion and the considerable degree of approval given to the scheme advocated in the paper.

It is most encouraging to hear from Colonel Purves that the British Post Office is keenly interested in the proposals which I have put forward, and that steps are being taken to investigate the scheme with a view to giving it a practical trial. I am also glad to hear from the Engineer-in-Chief of the British Post Office that on the engineering side the scheme presents no serious difficulties, and that it is essentially an economic problem. That is a point upon which I have laid emphasis in the paper, and I am glad to have it confirmed by so high an authority. Colonel Purves makes a good point about the relative efficiencies of the receiving appliances in the case of the telephone and telegraph, in the one case the enormously sensitive and intelligent human ear, and in the other case inanimate and comparatively insensitive telegraph apparatus. My reply is that vacuum tubes now far exceed in sensitiveness the human ear, and that there is no reason why all the telephone methods (including vacuum tubes) should not be applied to telegraphy. It is a physical impossibility to avoid the consequences of the facts displayed in Fig. 1. In any case the margin of about 100 to 1 in favour of the telegraph and against the telephone is so great that heavy discounts can be allowed in respect to points such as that to which Colonel Purves has referred.

Another point made by Colonel Purves is that he is not impressed with the suitability of the printing-telegraph for sending and receiving service switching instructions, and he is evidently not prepared to shut out the possibility of combining the teletype and telephone, switching from the one to the other at will. I am glad to hear that, and two French inventions appear to make it practicable to work start-stop printers through ordinary telephone exchanges in conjunction with telephones.

The criticisms by Mr. Newlands are also very helpful. I agree with him that the present cost of start-stop printers is far too high. It is a new industry, however, and the preliminary expenses have been heavy. When the industry begins to pay its way, prices will come down. That has been the experience in all industries. It is very encouraging to have the opinion expressed by Mr. Newlands that when prices come down, as the result of bulk manufacture of start-stop printers in this country these machines will make very rapid progress indeed. Mr. Newlands refers to what I have called "bottle-necks" —points where telegraph messages accumulate and have to wait their turn. That, of course, would prevent direct communication; but the telegraph service at present is full of bottle-necks, with consequential delays and waste of labour in writing down telegrams, and it is one of the attractions of the printing-telegraph exchange idea that it will greatly reduce the number of bottle-necks, and possibly in time abolish them altogether.

I admit that to work over 5 000 miles with the teletype is rather idealistic under present conditions; but it is not impossible, because the Western Union Company is working six multiplex installations on six telegraph wires right across the American continent, a distance of about 3 300 miles. Each of these wires is carrying 100 words a minute simultaneously in each direction. Under these circumstances, to work the teletype at 40 words a minute over 5 000 miles presents no technical difficulty at all. In fact, on wires 3 000 miles long it will be easy to have two teletype channels simultaneously in each direction on one wire, a result eight times cheaper than the telephone, even if the telephone could work over such a distance with no more costly technical appliances than the telegraph, a thing that it certainly cannot do.

The points raised by Mr. Shaughnessy are also good. Certainly the price of start-stop printers will have to come down very much before there can be any great extension of their use; but the present high prices are the main factor that will render it possible by and by to get the price down to a point much below the present rate. Capital must be accumulated to make cheap manufacture possible, and the manufacture of such machines must first reach the remunerative stage. That condition has not yet been fulfilled.

Mr. Kingsbury's remarks are specially interesting because they express the telephone point of view. His analogy with passenger and goods traffic on railways is illuminating and is rather adverse to the teletype exchange scheme, though he agrees that it is a question of cost and convenience. It is very instructive to hear that the telegraph exchange plan was patented as far back as 1851, because it is remarkable to note how many good ideas have been published and forgotten long ago, the time not having been ripe for them. In my paper I have taken the same line as Mr. Kingsbury in favouring separate teletype exchanges; but it is a point about which there appears to be considerable difference of opinion, especially in view of the two French inventions to which I have referred and in view of the wonderful capabilities of vacuum valves.

One point mentioned by Mr. Johnson is the difficulty

about switching over from short to long lines. This certainly makes it difficult to apply the duplex balance in every instance; but in the case of simplex working there is no more difficulty in switching the teletype rom short to long lines than in the case of the morse key and sounder. I am glad that Mr. Johnson draws attention to the waste of labour, inevitable under the present system, of writing down telegrams and rewriting them several times. That is one of the strong points in favour of the teletype exchange. As for the cost of labour at switching centres, referred to by Mr. Johnson, it seems to be not unlikely that automatic telephone exchange machinery will take care of this difficulty.

An important point was raised by Mr. Thompson about my comparison of telephone and telegraph signalling in Fig. 1. The harmonics giving practically square-shaped telegraph waves certainly would reduce the ratio of 365 : 21; but telegraphy with the fundamental frequency only and without any serious admixture of upper harmonics is possible, and has indeed been advocated by Rowland, Squier and others. In any case the number of different harmonics in line A, Fig. 1, must of necessity be very large, and line D makes some approach to one fundamental frequency. The unavoidable difficulty, so far as telegraphy is concerned, appears to me to be not harmonics but the changes of phase in the waves, which have to be made in order to transmit signals, because a pure sine-wave alternating current cannot transmit intelligence. For instance, in line D (Fig. 1) a half wave has been suppressed at P, thus throwing the succeeding waves completely out of step. In the next letter, A, a half wave has been reversed from negative to positive. These changes of phase cannot be good for telegraphy when filter methods are employed; but telegraphy is impossible without either such changes of phase or changes in amplitude. Experience has shown that the latter are inadmissible, so we are left with changes of phase as the only practicable method of telegraphy. Just what effect this has on the comparison in Fig. 1 I do not know; but the facts mentioned by Mr. Thompson indicate that it may be considerable. The figures given by him, in regard to the number of channels into which a telegraph wire can be split up by the Western Electric Co.'s methods, are astonishing and confirm the arguments in the paper. Mr. Thompson raises another important point, namely, a universal 5-unit telegraph code. That is a matter which will have to receive the attention of the telegraph administrations in the near future.

Major Masters, in suggesting that the telephone-telegraph combination would give some of the advantages which I have put forward for the teletype exchange scheme in a more simple manner, appears to me to have overlooked the economic consequences of Fig. 1 and the saving in labour in telegraph offices by the teletype combined with teletype exchanges. That is impossible of achievement by the telephone-telegraph combination.

Mr. Thorrowgood raises the point about the difficulty of using the teletype, compared with the telephone. The same argument applies to the typewriter. Business men do not use typewriters: they dictate their letters and telegrams now, and the only change will be that they will dictate more telegrams and fewer letters, and their typists will be as expert on the keyboards of the teletypes as they are now on the same keyboards of typewriters.

Mr. Brown's suggestion about combining the phonograph with the telephone is unfortunately not practicable, and it also disregards the economic consequences of Fig. 1.

Mr. Stuart Jones pointed out that the first newspaper paragraph quoted by me does not apply to the British telegraph system. In reply I may point out that my paper deals with telegraphy throughout the world, and not only with the British and one or two other telegraph services which are relatively good. I am sorry to say Mr. Stuart Jones is right in asserting that the British public (and, I may add, also the American) are not dissatisfied with the telegraph service. My point is that they ought to be, and my paper has been written to inspire the public with a little divine discontent on the subject. I want to galvanize the public into demanding something far better not only for themselves but also for the telegraph administrations.

Mr. Stuart Jones makes a good point about the danger of putting all one's eggs into one basket; but the risk depends on the kind of basket. Underground circuits are wonderfully reliable and weatherproof. As I have pointed out in reply to another speaker, it is not business men but their typists who will do the telegraphing.

Mr. Findley, like several other speakers, has concentrated his attention too much on England. I wrote for the world and not only for Great Britain; I took a cosmopolitan view. Several speakers expressed doubt about the farmer ever using the teletype. Mr. Johnson, for instance, said that English farmers are too conservative to use the teletype; but if he will refer again to pages 254 and 255, he will find that I expressly exempted the British farmer and mentioned farmers in other parts of the world, particularly in America, as probable very large users of the teletype. Again, a careful study of the economic consequences of Fig. 1 will show Mr. Findley the need for teletyping, in spite of our being able to teletalk with efficiency and economy. Distances are short in Great Britain, and there is no reason why Mr. Findley's visions of a greatly improved telephone service in this country should not be realized; but the great new countries of the world, the United States, Canada, South Africa, Australia, Russia, Siberia and South America have very long distances, which make the economic consequences of Fig. 1 very important indeed.

I welcome the support given to my forecast of telegraph development by Mr. Herbert, whose paper was most suggestive. It made no mention, however, of the idea of getting every business man to do his own telegraphing, just as he does his telephoning, direct to his correspondents through teletype exchanges. That is the essence of my paper. Mr. Herbert stresses the fact that it is the cost of labour that makes telegrams costly. Obviously the remedy is to abolish the costly labourers—the middlemen workers—and transmit and receive tele-

grams direct. I note with interest that Mr. Herbert, like many other Post Office engineers, is a supporter of automatic switching for the proposed teletype exchanges.

In conclusion, I should like to draw attention to a probable method of using the teletype efficiently through teletype exchanges, namely, storing up messages and sending them through by teletype on one call. Business men already do this in the case of long-distance telephone calls, when these are a daily occurrence. They note down beforehand points for discussion when the telephone call is put through, and it seems likely that telegrams to be sent by the teletype through exchanges will be typed ready to be sent through on one call, which may last for 10 or 12 minutes. In that time two expert typists would easily exchange 500 words between two offices 1 000 miles apart, and on a line equipped with the duplex balance the number of words could be raised to 1 000. This method of working would greatly increase the efficiency of the teletype exchange by increasing the ratio of profitable working time compared with the time spent in getting connected.

THE PREDETERMINATION OF THE PERFORMANCE OF INDUCTION MOTORS.*

By D. B. HOSEASON, Associate Member.

(*Paper first received 1st September, and in final form 23rd October, 1924.*)

SUMMARY.

The accuracy with which the performance of induction motors can be forecast in actual practice has not yet reached that attained in connection with other types of machines. An indication of this lies in the recognized tolerances on guarantees, especially those on power factor. The inaccuracies do not arise from ignorance of the conditions on the designer's part but rather from lack of time to take into account all the factors.

This paper is intended to describe a quick yet accurate means of predetermining the performance of induction motors. A group of accurate formulæ is developed on the basis outlined by Steinmetz and is given alongside the corresponding approximate formulæ which have hitherto been much used on account of their simplicity. Curves are then drawn showing the difference between the results given by the two groups of formulæ, the ratios being expressed as correction factors. It is thus possible to obtain results approaching the accuracy of the more involved systems of calculation, by using the simplest formulæ and applying the appropriate correction.

Finally, two examples are given indicating the accuracy obtained by the use of the curves.

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(1) INTRODUCTION.

It has often been pointed out that by using the graphic method of "inversion," or the exact mathematical method outlined by Steinmetz, the performance of induction motors can be predetermined with greater accuracy than by using more common methods. The labour involved, however, in using either system has so far prevented their adoption in the engineering and design departments of most firms.

The circle diagram in its simplest form is based on a constant value of magnetizing current from standstill to synchronism and also takes no account of the change in phase angle between the mutually induced E.M.F. in the primary winding and the applied voltage. The calculation of the performance of a motor on a basis of this simple circle diagram can be easily and rapidly carried out and has already been reduced to the application of a number of well-known formulæ.

The method here suggested for predetermining the performance of an induction motor is an endeavour to obtain the accuracy of the more involved systems with the rapidity of application of the simplest.

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

(2) The Polyphase Induction Motor Equivalent Circuit.

It is perhaps advisable to refer to the terms used and to show their relationship. Fig. 1 shows the equivalent circuit diagram of a polyphase induction motor. r_1 and x_1 combined correspond to the primary self-inductive impedance, x_1 relating to that flux which links the primary winding only and more commonly called primary leakage flux. r_2 and x_2 similarly correspond to the secondary self-inductive impedance, where x_2 relates to that flux which links the secondary winding only, generally termed secondary leakage flux. r_m and x_m correspond to the mutual inductive impedance, or the impedance of the magnetizing circuit. r_m is the wattful component required for iron losses, and x_m relates to the flux linking both windings, generally termed main flux.

The actual values of r_2 and x_2 are expressed in terms of the primary winding, and in the case of x_2 also in terms of the supply frequency. The secondary reactance is a variable quantity depending on the frequency of

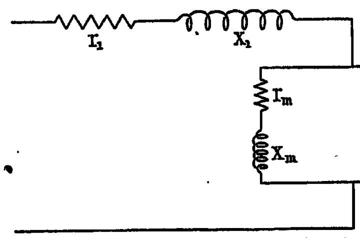

Fig. 1.—Equivalent circuit diagram for a polyphase induction motor.

the secondary currents and thus the slip s. Then we have :—

Primary self-inductive impedance $= r_1 + jx_1 = \dot{Z}_1$*
Secondary self-inductive impedance $= r_2 + jsx_2 = \dot{Z}_2$
Mutual inductive impedance $= r_m + jx_m = \dot{Z}_m$

the following example, which shows the method of deducing the primary current at any slip.

If $\dot{I}_1$ = primary current ; $\dot{E}_1$ = applied voltage ;
$\dot{I}_2$ = secondary current ; $\dot{E}_2$ = mutually induced E.M.F. in the primary winding

Then $$\dot{E}_1 = \dot{E}_2 + \dot{I}_1(r_1 + jx_1) \quad . \quad . \quad . \quad (1)$$

$\dot{I}_1$, however, has two components, the secondary current and the magnetizing current, and

$$\dot{I}_1 = \dot{I}_2 + \frac{\dot{E}_2}{r_m + jx_m}$$

The E.M.F. generated in the secondary, due to the secondary conductors slipping back through the field, is $s\dot{E}_2$.

Then $$\dot{I}_2 = \frac{s\dot{E}_2}{r_2 + jsx_2}$$

and $$\dot{I}_1 = \frac{s\dot{E}_2}{r_2 + jsx_2} + \frac{\dot{E}_2}{r_m + jx_m}$$

$$= \dot{E}_2\left[\frac{s}{r_2 + jsx_2} + \frac{1}{r_m + jx_m}\right] \quad . \quad . \quad (2)$$

Substituting this value of I_1 in equation (1) we have :—

$$\dot{E}_1 = \dot{E}_2 + \dot{E}_2(r_1 + jx_1)\left[\frac{s}{r_2 + jsx_2} + \frac{1}{r_m + jx_m}\right]$$

$$= \dot{E}_2\left[1 + \left\{\frac{s(r_1 + jx_1)}{r_2 + jsx_2} + \frac{(r_1 + jx_1)}{r_m + jx_m}\right\}\right]$$

$$\dot{E}_2 = \frac{\dot{E}_1}{\left[1 + \left\{\frac{s(r_1 + jx_1)}{r_2 + jsx_2} + \frac{r_1 + jx_1}{r_m + jx_m}\right\}\right]}$$

Substituting in Equation (2) we obtain :—

$$\dot{I}_1 = \dot{E}_1\frac{s(r_m + jx_m) + (r_2 + jsx_2)}{(r_2 + jsx_2)(r_m + jx_m) + (sr_1 + jsx_1)(r_m + jx_m) + (r_1 + jx_1)(r_2 + jsx_2)}$$

$$= \dot{E}_1\frac{(sr_m + r_2) + j(sx_m + sx_2)}{[r_2(r_m + r_1) + s(r_1r_m - x_mx_t - x_1x_2)] + j[r_2(x_m + x_1) + s(r_mx_t + r_1x_m + r_1x_2)]}$$

For convenience of expression let

$$r_1 + r_2 = r_t$$
$$x_1 + x_2 = x_t$$
$$\dot{Z}_1 + \dot{Z}_2 = \dot{Z}_t$$

(3) The Primary Current of an Induction Motor.

Col. 1 of the table (p. 282) gives a number of formulæ corresponding to the simple circle diagram already mentioned, while col. 2 shows the more accurate formulæ which take full account of the change in magnetizing current and change of phase angle between the mutually induced E.M.F. in the primary and the applied voltage with change of speed. The general method of obtaining these expressions is indicated in

* Symbolic values are denoted $\dot{Z}_1$, $\dot{Z}_2$, etc., and virtual values Z_1, Z_2, etc.

The denominator of this expression occurs repeatedly throughout all the various equations relating to the motor, and for convenience the individual items are expressed by the following constants :—

$\alpha = r_2(r_m + r_1)$; $\beta = r_1r_m - x_mx_t - x_1x_2$;
$\rho = r_2(x_m + x_1)$; $\mu = r_1x_m + r_mx_t + r_1x_2$.

Then $$\dot{I}_1 = \dot{E}_1\frac{(sr_m + r_2) + j(sx_m + sx_2)}{(\alpha + \beta s) + j(\rho + \mu s)}$$

the virtual value of which is

$$I_1 = E_1\sqrt{\left[\frac{(sr_m + r_2)^2 + (sx_m + sx_2)^2}{(\alpha + \beta s)^2 + (\rho + \mu s)^2}\right]}$$

The torque formula is obtained in a similar manner

TABLE.

INDUCTION-MOTOR PERFORMANCE FORMULÆ.

	(1) APPROXIMATE FORMULÆ	(2) CORRECT FORMULÆ
Primary current at any slip s ..	$E_1\sqrt{\left[\frac{(r_2+sr_1+sr_m)^2+(sx_t+sx_m)^2}{(r_2r_m+sr_1r_m-sx_mx_t)^2+(sr_mx_t+sr_1x_m+r_2x_m)^2}\right]}$	$E_1\sqrt{\left[\frac{(sr_m+r_2)^2+(sx_m+sx_2)^2}{(\alpha+\beta s)^2+(\rho+\mu s)^2}\right]}$
Secondary current at any slip s ..	$\frac{sE_1}{\sqrt{[(r_2+sr_1)^2+s^2x_t^2]}}$	$\frac{sE_1Z_m}{\sqrt{[(\alpha+\beta s)^2+(\rho+\mu s)^2]}}$
Torque at any slip s	$\frac{sE_1^2r_2}{(r_2+sr_1)^2+s^2x_t^2}$	$\frac{sE_1^2r_2Z_m^2}{(\alpha+\beta s)^2+(\rho+\mu s)^2}$
Maximum torque	$\frac{E_1^2}{2[r_1+\sqrt{(r_1^2+x_t^2)}]}$	$\frac{E_1^2r_2Z_m^2}{2\{\alpha\beta+\rho\mu+\sqrt{[(\alpha^2+\rho^2)(\beta^2+\mu^2)]}\}}$
Slip at maximum torque	$\frac{r_2}{\sqrt{[r_1^2+x_t^2]}}$	$\sqrt{\left[\frac{\alpha^2+\rho^2}{\beta^2+\mu^2}\right]}$
Power at any slip s	$\frac{s(1-s)E_1^2r_2}{(r_2+sr_1)^2+s^2x_t^2}$	$\frac{s(1-s)E_1^2r_2Z_m^2}{(\alpha+\beta s)^2+(\rho+\mu s)^2}$
Maximum power	$\frac{E_1^2}{2(Z_t+r_t)}$	$\frac{E_1^2r_2Z_m^2}{2\left\{\alpha\beta+\rho\mu+(\alpha^2+\rho^2)\left[1+\sqrt{\left(\frac{(\alpha+\beta)^2+(\rho+\mu)^2}{\alpha^2+\rho^2}\right)}\right]\right\}}$
Slip at maximum power	$\frac{r_2}{Z_t+r_2}$	$\frac{1}{1+\sqrt{\left[\frac{(\alpha+\beta)^2+(\rho+\mu)^2}{\alpha^2+\rho^2}\right]}}$

Z_1 = Primary self-inductive impedance.
Z_2 = Secondary self-inductive impedance.
Z_m = Mutual inductive impedance.

$Z_1 = r_1 + jx_1$; $Z_1 + Z_2 = Z_t$
$Z_2 = r_2 + jx_2$; $r_1 + r_2 = r_t$
$Z_m = r_m + jx_m$; $x_1 + x_2 = x_t$

$\alpha = r_2(r_m + r_1)$
$\beta = r_1r_m - x_mx_t - x_1x_2$

$\rho = r_2(x_m + x_1)$
$\mu = r_mx_t + r_1(x_m + x_2)$

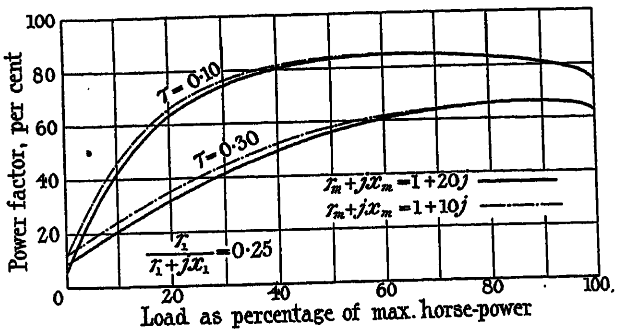

FIG. 2.—Curves showing the effect of iron loss on the power factor of an induction motor (short-circuit power factor = 0·25).

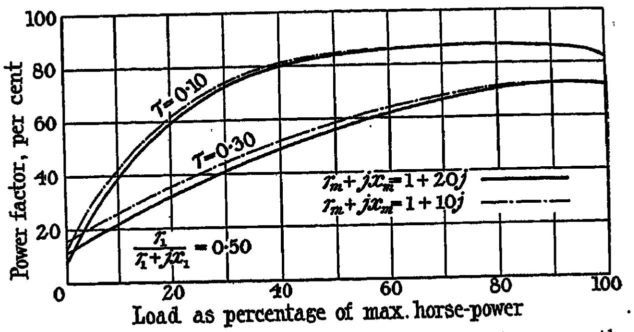

FIG. 3.—Curves showing the effect of iron loss on the power factor of an induction motor (short-circuit power factor = 0·5).

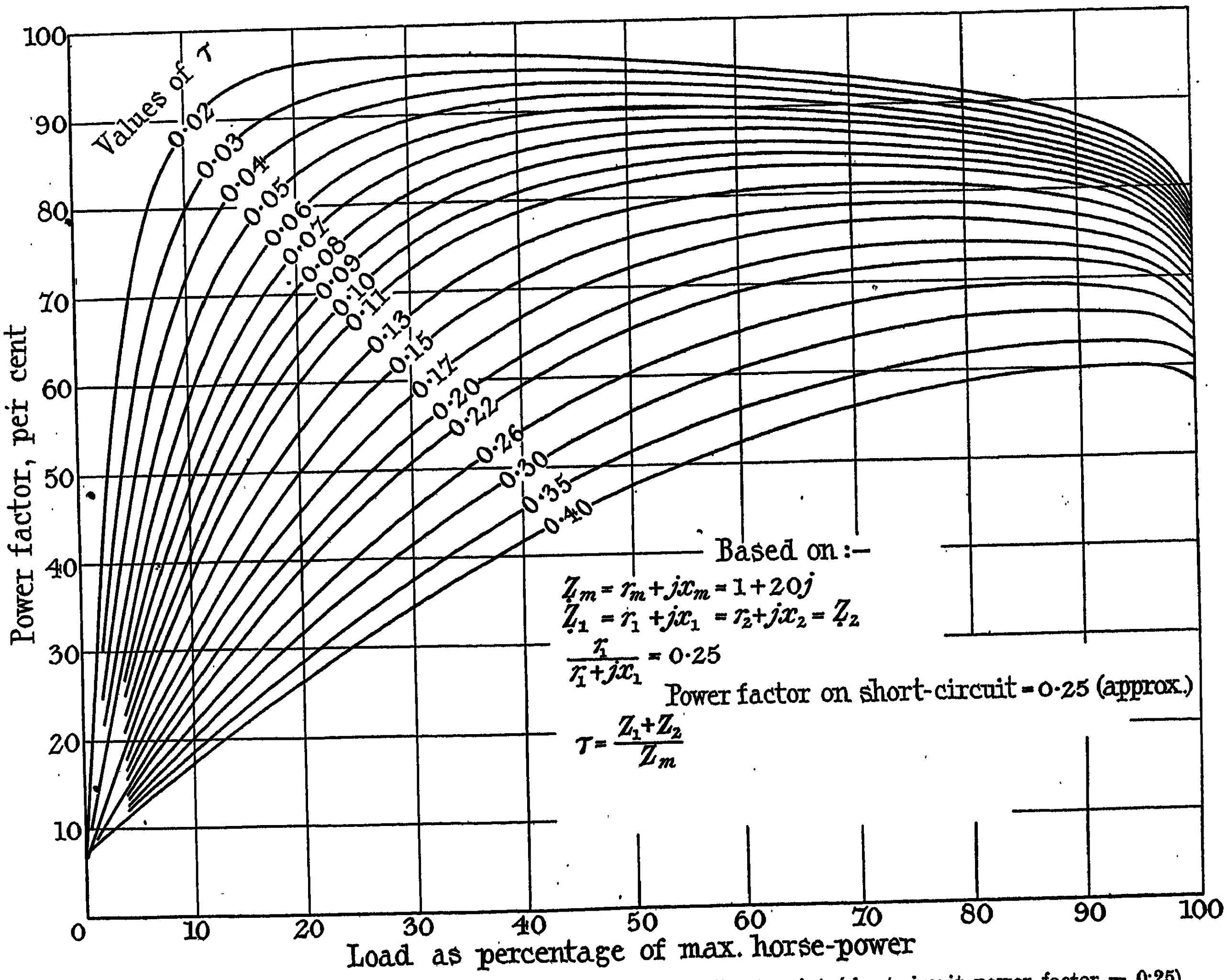

FIG. 4.—Induction-motor power factor curves from no-load to pull-out point (short-circuit power factor = 0·25).

and from this, by differentiation, the slip for maximum torque, and thus the maximum torque is also deduced. By multiplying by $(1 - s)$ an expression for power output is obtained from the torque formula, and, again by differentiating, the slip for maximum power is obtained and thus the maximum power.

(4) INDUCTION-MOTOR PERFORMANCE CURVES.

The extent of the difference between the results given by the two groups of formulæ depends on the ratio of working out the power factors from the primary current formula in column 2 of the table for the various sets of conditions, a complete group of curves can be produced which will enable the power factor of a motor to be determined at any load. These curves would take into consideration all the conditions governing the motor power factor, such as change in magnetizing current due to primary impedance drop, and change of phase angle of the primary back E.M.F.

In order to produce the curves mentioned above,

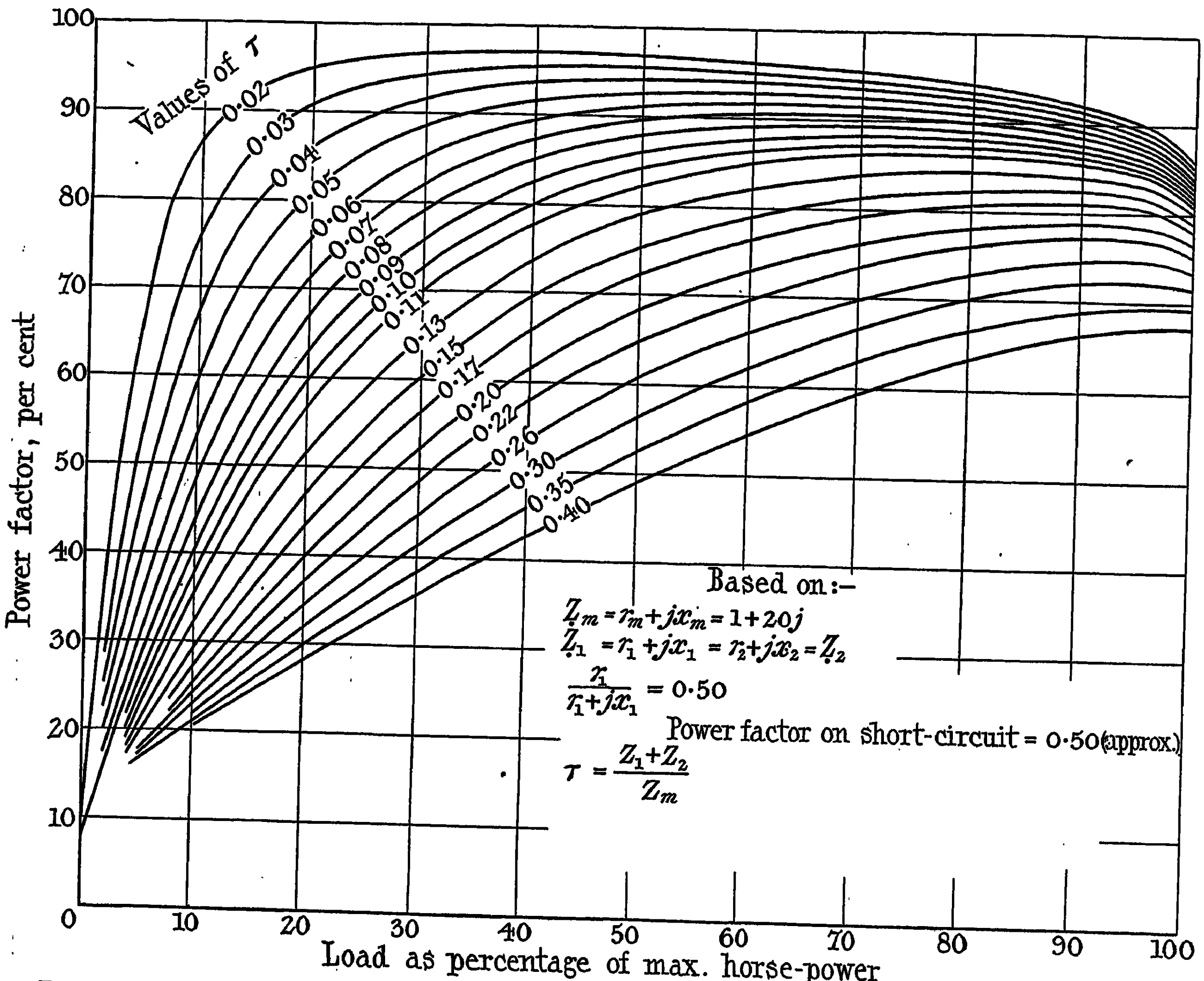

FIG. 5.—Induction-motor power factor curves from no-load to pull-out point (short-circuit power factor = 0·5).

the mutual inductive impedance to the total self-inductive impedance. For example, in the case of a motor with a comparatively small magnetizing current the results obtained will be almost the same from both formulæ. For machines with a large amount of magnetizing current, however, the results obtained may differ widely. If curves are plotted on the basis of the ratio of the mutual to the total self-inductive impedance, it is possible to obtain a series of correction factors for the approximate formulæ which will enable the correct figures to be obtained. Furthermore, by certain assumptions must be made. First, the primary and secondary impedances at the line frequency are assumed to be equal. This is usually not far wrong, and the errors likely to occur from the assumption will be small. Secondly, the power factor in the magnetizing circuit must be fixed. An analysis has been made of a number of tests on machines varying from ½ h.p. to 200 h.p. and the limits of power factor variation in the magnetizing circuit appear to be from 0·05 to 0·10. This power factor is really an indication of the proportion of iron loss in the machine, and its effect

on the overload capacity and short-circuit current of the motor will be negligible. The effect on the total power factor is shown in Figs. 2 and 3 for two values of τ in each case, where $\tau = Z_t/Z_m$.

The majority of the tests analysed were nearer the power factor of 0·05 than 0·10, and as this figure causes the estimated results to be slightly on the low side it has been used in compiling the remaining curves.

A third assumption which must be made is the power factor of the self-inductive circuits at the supply frequency. This usually lies between 0·25 and 0·50. If, then, two sets of curves are available for power factors of 0·25 and 0·5 respectively, by using both curves and making allowance for the difference according to the exact figure for the self-inductive power factor, comparatively accurate results can be obtained.

On the basis of the above assumptions two sets of curves have been drawn in Figs. 4 and 5, giving induction-motor power factors at all loads from no load to the "pull out" point and for values of τ from 0·02 to 0·40. Similarly the maximum powers have been worked out, using the two formulæ given in cols. 1 and 2 of the table, and the relationship is plotted in Fig. 6. The maximum power calculated from formula (1) has been called the "apparent" maximum, and that obtained by formula (2) the "actual" maximum. In the case of these curves and with the higher values of τ it will be observed that quite an appreciable reduction in estimated overload capacity occurs. To take an extreme case, a motor might have an apparent overload capacity of 1·75 times full load momentarily, whereas the actual figure could be as low as 1·35 to 1·40 times full load. Fig. 7 has been drawn with the object of indicating the effect of the magnetizing-current component of the short-circuit current. It is generally stated that the short-circuit current is given by dividing the impressed voltage by the total self-inductive impedance, or, alternatively, that the total

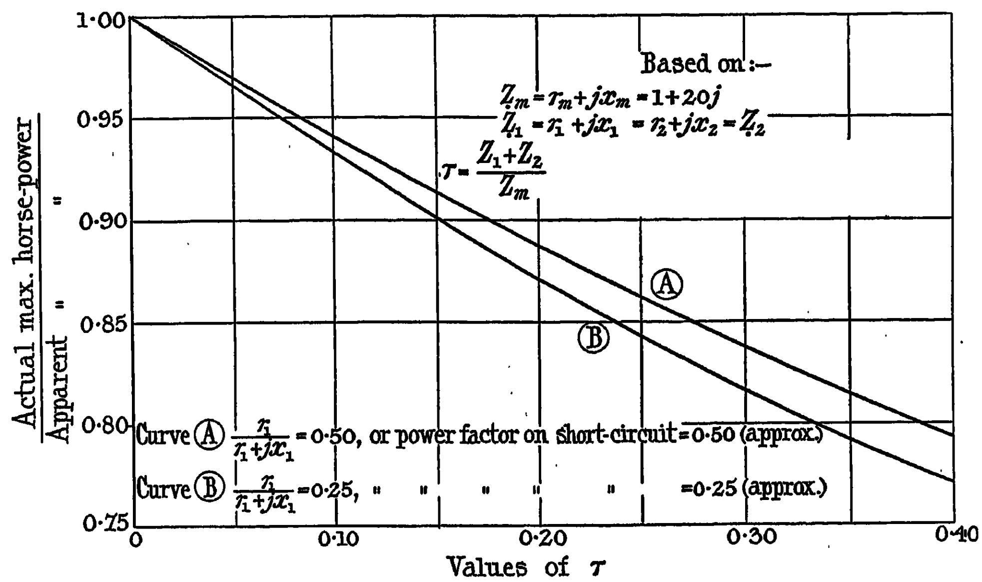

FIG. 6.—Curves showing actual and apparent maximum horse-power.

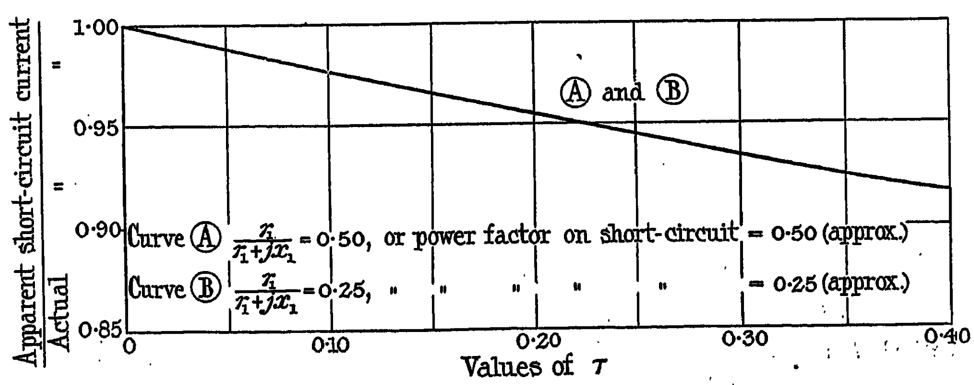

FIG. 7.—Curves showing actual and apparent short-circuit current.

self-inductive impedance is given by dividing the impressed voltage by the short-circuit current. This statement has generally been qualified by assuming a normal relationship between Z_t and Z_m, and it has been pointed out that some of the current measured on short-circuit is actually magnetizing current. In Fig. 7 the current obtained by dividing the impressed voltage by Z_t has been termed "apparent" short-circuit current, while that obtained by working out the formula in col. 2 of the table for $s = 1 \cdot 0$ has been termed "actual" short-circuit current. The results indicate that this point is of no very great consequence, as the actual numerical values in the worst case are only about 8 per cent in error. The variations in self-inductive impedance due to differences in manufacture are often of this order or greater.

The method of applying the curves in actual practice is as follows. After the completion of the customary preliminary designs and when the actual windings have been fixed, the magnetizing current and leakage flux are estimated in the usual way. The iron loss is then determined and the values of r_m and x_m are found. It should be noted that when the power factor is as low as $0 \cdot 05$ to $0 \cdot 10$ the numerical difference between the reactance and impedance is so small that the ohmic values of r_m and x_m are given by :—

$$r_m = \frac{P}{I_m^2}; \quad x_m = \frac{E}{I_m}$$

where E = the voltage considered in estimating P and I_m,
I_m = the estimated magnetizing current, and
P = the estimated iron loss, in watts.

The resistances of the primary and secondary windings are next calculated and that of the secondary referred to the primary. From the leakage flux the total motor reactance is determined, and finally the total self-inductive impedance Z_t and the value of τ. The apparent maximum horse-power is calculated in line with col. 1 in the table and then from Fig. 6 the appropriate correction factor is determined. Using the actual maximum horse-power and knowing the value of τ, the motor power factor at any load can be found from Figs. 4 and 5. The remainder of the performance data, i.e. slip, losses and efficiency, are determined in the usual way.

(5) Tests and Conclusions.

The two following examples indicate the results obtained by the application of the curves. The results given under method 1 are obtained by using the approximate formulæ given in col. 1 of the table, and those under method 2 show the effect of applying the correction factors.

(1) $3\frac{1}{2}$ *h.p., three-phase, 50-period, 400-volt, 715-r.p.m. slip-ring motor for crane service.* Half-hour rating.

$$r_m + jx_m = 2 + 38j; \quad Z_m = 38$$
$$r_t + jx_t = 4 \cdot 6 + 9 \cdot 0j; \quad Z_t = 10 \cdot 1$$
$$r_t/Z_t = 0 \cdot 46; \quad \tau = 0 \cdot 266$$
Volts per phase = 231.

	Method 1	Method 2	Test
Maximum horse-power	2·08 × full load	1·75 × full load	—
Full-load power factor	0·55	0·63	0·65
$\frac{3}{4}$ load power factor ..	0·46	0·54	0·55
$\frac{1}{2}$ load power factor ..	0·35	0·42	0·43

(2) 60 *h.p., three-phase, 50-period, 415-volt, 322-r.p.m. slip-ring motor.* Standard 6-hour rating.

$$r_m + jx_m = 1 \cdot 14 + 15 \cdot 6j; \quad Z_m = 15 \cdot 6$$
$$r_t + jx_t = 0 \cdot 50 + 2 \cdot 56j; \quad Z_t = 2 \cdot 6$$
$$r_t/Z_t = 0 \cdot 19; \quad \tau = 0 \cdot 166$$
Volts per phase = 415.

	Method 1	Method 2	Test
Maximum horse-power	1·86 × full load	1·65 × full load	—
Full-load power factor	0·74	0·76	0·77
$\frac{3}{4}$ load power factor ..	0·69	0·71	0·73
$\frac{1}{2}$ load power factor ..	0·58	0·60	0·62

In using the curves the assumptions upon which they are based should be kept in view as, although accurate results are obtained over a wide range, occasional cases will occur in which, for example, the primary impedance differs considerably from the equivalent secondary impedance, or the iron loss is excessive. The friction, windage and tooth-frequency iron losses all require an output torque from the secondary and should consequently be added to the load to obtain the total secondary output. In highly saturated machines the power factor will be slightly higher than that given by the curves, as a small increase in the primary drop will result in considerable reduction in magnetizing current.

A NEW TYPE OF SQUIRREL-CAGE INDUCTION MOTOR WITH HIGH STARTING TORQUE.

By T. F. WALL, D.Sc., D.Eng., Associate Member.

(*Paper first received* 15*th July, and in final form* 26*th November*, 1924; *read before the* SHEFFIELD SUB-CENTRE 17*th December*, 1924.)

SUMMARY.

This paper contains an account of tests made on a new type of squirrel-cage induction motor with high starting torque. Each conductor of the rotor winding is a compound bar of which the characteristic property is that the resistance increases with the frequency of the alternating current flowing in it.

The compound bars are each built up as follows: There is a central core of copper, which is surrounded by a sleeve of steel. Outside the steel sleeve is a skin of copper, the outer copper skin and the central copper core being brought into good electrical contact at each end. When alternating current flows through the compound conductor the portion passing through the central copper core produces in the steel sleeve a magnetic flux which induces a back E.M.F. tending to choke the current out of the core. The result is that the current will flow chiefly through the high-resistance copper skin outside the steel sleeve. The greater the frequency of the alternating current the greater will be the back E.M.F., and the effective resistance of the compound bar will be correspondingly increased.

If a squirrel-cage rotor winding is formed from these compound conductors, then, at starting, since currents of the full supply frequency will flow in the bars, the effective resistance and the starting torque will be high. When running normally, the currents in the rotor bars will be at the very low frequency of slip and hence the resistance will be correspondingly low; in fact, it will be practically the same as the resistance as measured by direct current.

The paper contains the results of tests made on a squirrel-cage rotor built with compound conductors in accordance with the author's proposals, and also the test-results on a standard rotor, the same stator being used in each case.

TABLE OF CONTENTS.

INTRODUCTORY.

The squirrel-cage induction motor is probably the simplest, most robust, and cheapest machine yet invented for transforming energy. The great defect, however, under which this type of machine suffers and which is seriously retarding its full exploitation, is the fact that if it is started by being switched directly on to the supply mains there will be a heavy initial rush of current in the line. Since this starting current has a low power factor the voltage regulation of the supply mains might be seriously affected if no limitations as to the size and number of such squirrel-cage motors were to be enforced.

The electric supply undertakings in this country and on the Continent are not favourably disposed to the installation of squirrel-cage induction motors in any but the smallest sizes unless means are provided for limiting the rush of current in the line at starting.

The standard methods used in practice for complying with this requirement result in a very poor starting torque, so that the motor cannot start under full load. It therefore becomes necessary either to provide a fast-and-loose pulley arrangement, or to fit some form of centrifugal clutch so that the load is not applied until the motor reaches full speed or nearly full speed. Such accessories, however, cannot but deprive the squirrel-cage motor of its most striking inherent characteristics of cheapness, simplicity and robustness, and consequently this type of motor has not taken the place to which it is naturally entitled in the industrial applications of the electrical drive.

In this paper the author describes a new method of providing a squirrel-cage motor with a high starting torque without necessitating a prohibitively large starting current in the line. It is hoped that these proposals may point the way to the definite solution of this long-standing and troublesome practical problem.

THEORY.

It is generally recognized that the proper solution of the problem of high starting torque and low starting current is the use of a high resistance in the rotor circuit at starting. An inspection of the formula* for the torque of an induction motor shows that the starting torque is, within limits, almost directly proportional to the rotor resistance, and it is also obvious that the starting current will be reduced as the rotor resistance is increased.

When a wound rotor provided with slip-rings is used, it is a simple matter to introduce resistances in series with the rotor winding at starting and to cut them out as the motor runs up to speed, so that eventually —when the motor has attained full speed—all the starting resistances have been cut out and the rotor winding has been short-circuited. The superior starting characteristics of wound rotors give them almost the monopoly of use in this country and on the Continent for all motors except those of the smallest sizes.

* *Journal I.E.E.*, 1923, vol. 61, p. 129.

For many years, attempts have been made to produce a squirrel-cage rotor which shall have a high effective resistance at starting and a low effective resistance when running, so that the good starting characteristics

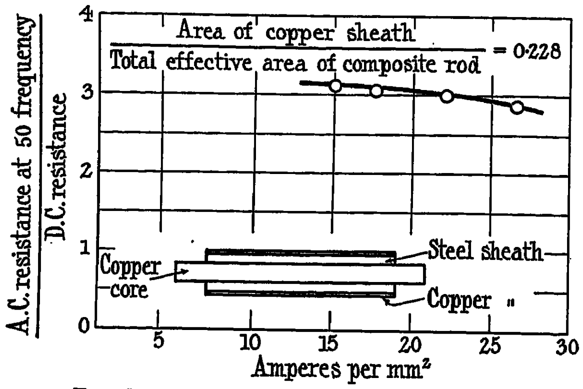

FIG. 1.—Current density in composite rod.

are not obtained at the expense of poor efficiency when running. References to the literature of the subject will show what a great variety of proposals have been made for this purpose but, so far as the author is aware, none of them has yet established itself in practice.

FIG. 2.

NOTE: The zero lines of the two waves are not coincident.

In the present paper, attention is concentrated on a method recently developed by the author which is considered to have advantages not possessed by any previous proposal. A number of test data have been obtained, which it is hoped may form the basis of the design of squirrel-cage rotors for any required practical conditions. The data given later in the paper have been obtained from an actual experimental motor of 57 b.h.p. built in accordance with the author's proposals by Messrs. J. H. Holmes and Co. and tested by them at their works in Newcastle-on-Tyne.

Before proceeding to the consideration of the rotor construction as proposed by the author, a short review of previous cognate work will be given.

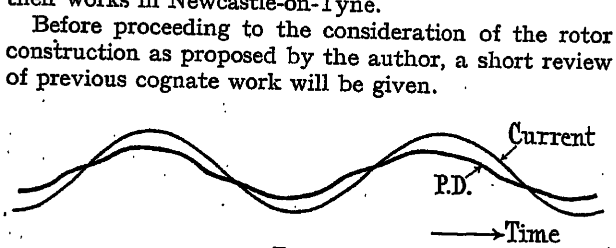

FIG. 3.

NOTE: The zero lines of the two waves are not coincident.

In the year 1900 H. M. Hobart proposed to make use of the "skin effect" in iron for improving the starting characteristics of squirrel-cage rotors, and for this purpose he proposed the use of iron rotor bars. The idea was that at starting, the frequency of the rotor currents being the full supply frequency, the skin effect in the iron conductors would cause them to have a high effective resistance at starting. When, however, the motor is running at full speed, the frequency of the currents in the rotor bars will be the frequency of the rotor slip, and will therefore be so small that the skin effect becomes very slight, so that the resistance of the rotor winding is not much different from the value which would be obtained if measured for direct current. In accordance with this proposal, therefore, the rotor resistance would be automatically altered in accordance with the requirements and the rotor construction would lose none of its robustness, simplicity or cheapness.

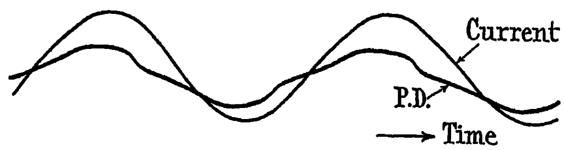

FIG. 4.

NOTE: The zero lines of the two waves are not coincident.

For several reasons this proposal has not met the practical requirements and, so far as the author is aware, has not been used on a commercial scale.

In 1915 Elihu Thomson proposed to make use of the

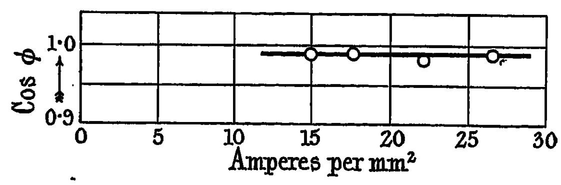

FIG. 5.—Current density in composite rod.

skin effect by means of special compound bars for the rotor winding. The bars were to be constructed of a central copper core surrounded by a steel sheath. At starting, the high-frequency currents, by reason of the back E.M.F. induced in the central copper core and

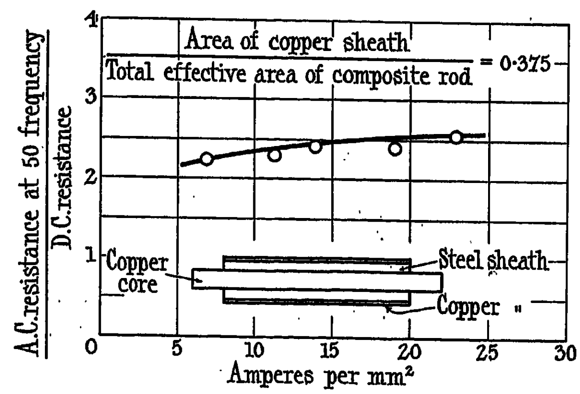

FIG. 6.—Current density in composite rod.

due to the magnetic field in the surrounding steel sheath, would be forced into the steel sheath so that very little current would flow in the central copper core. In this way the composite bar would be caused to have a high effective resistance when the motor was starting. When the frequency of the rotor currents

was reduced to the frequency corresponding to the rotor slip, the back E.M.F. induced in the central copper core would be correspondingly reduced so that practically all the current would flow in the central copper core, thus giving a low resistance when the motor is running.

Although this was a great advance on Hobart's original proposal, it has not met the practical requirements and the author believes that it has not been used to any extent. The reasons for this will be more apparent after a consideration of the test data given below, which have been obtained from an actual composite conductor constructed in accordance with the principle just stated.

The essential features of the method proposed by the author were described in a preliminary paper read before Section G of the British Association at Liverpool in 1923. Briefly stated, each rotor conductor is in effect a simple form of auto-transformer. It is well known, from the theory of transformers, that when the secondary winding is short-circuited the effective resistance of the primary winding is given by the expression

$$R_1 + \frac{M^2 R_2 \omega^2}{(L_2\omega)^2 + R_2^2}$$

where R_1 = resistance of the primary winding, in ohms,
R_2 = resistance of the secondary winding, in ohms,
L_2 = inductance of the secondary winding, in henrys, and
$\omega = 2\pi \times$ supply frequency.

This expression for the effective resistance of the primary winding shows that the resistance *increases* as the supply frequency increases.

Further, the effective inductance of the primary winding when the secondary is short-circuited is given by the expression

$$L_1 - \frac{L_2 M^2 \omega^2}{(L_2\omega)^2 + R_2^2}$$

where L_1 = inductance of the primary winding.

This expression shows that the effective inductance of the primary winding when the secondary is short-circuited *decreases* as the supply frequency increases.

Actually, each rotor bar is constructed as follows: A central copper core is surrounded by a steel sheath of suitable thickness which may or may not be in electrical contact with the copper core. The steel sheath is then covered with a copper skin of suitable sectional area and this outer copper skin is brought into good electrical contact at each end with the central copper core. A diagrammatic sketch of the composite rod is shown in Figs. 1 and 6. As already stated, such a composite conductor is, in effect, a simple form of auto-transformer with short-circuited secondary winding. The central copper core forms the primary winding, the steel sheath is the magnetic core, and the outer copper skin is the secondary winding.

If a squirrel-cage rotor is constructed with such composite bars, then, at starting, the frequency of the currents induced in the bars being of the full supply frequency, the effective resistance will be relatively high in accordance with the expression given above. When the rotor is running normally, the currents in the rotor bars will be of very low frequency corresponding to the rotor slip; consequently, the effective resistance of the composite bars will be correspondingly reduced and will, in fact, be practically the same as that found by direct-current measurement.

The relative thicknesses of the central copper core, the steel sheath, and the outer copper skin, are of great importance in determining a satisfactory performance and, in order to obtain a basis for the design and the predetermination of performance, a large number of tests have been carried out on composite rods of various proportions. A selection of these test-results are given below.

TESTS A.

Determination of the Influence of the Thickness of the Outer Copper Skin on the Characteristics of the Composite Rod.

For these tests the central copper core and the steel sheath were kept the same throughout and measurements were made of the characteristics for several different thicknesses of the outer copper skin. The dimensions of the central copper core and the steel sheath were as follows:

Diameter of central copper rod	5·9 mm
Cross-sectional area of central copper core	27·3 mm²
Radial thickness of steel tube	2·95 mm
Cross-sectional area of steel tube	84·0 mm²
Length of steel tube	20·3 cm

The steel tube was brought into good electrical contact with the central copper core at each end by soldering, so that the steel tube was effective in carrying a portion of the current, particularly at the very low frequencies.

The specific resistance of the steel used was 11 times that of copper, so that the equivalent area of the steel tube when referred to the conductivity of copper was 7·6 mm².

The total effective area of the central copper rod and the steel tube was therefore 34·9 mm².

(i) *Area of the outer copper skin* = 10·3 *mm*².—The total effective area of the composite rod in this case was consequently 45·2 mm², so that the ratio

$$\frac{\text{Area of outer copper skin}}{\text{Total effective area of composite rod}} = 0\cdot 228.$$

Tests were made of the effective resistance and the power factor of the composite rod when supplied with current of 50 frequency. The resistance measurements were made by means of a vacuum thermo-junction and galvanometer which was used to determine the potential difference across the rod when the alternating current was flowing, the thermo-junction and galvanometer being afterwards calibrated by direct current. The values of the power factor were ascertained from the oscillograms of the P.D. and current waves.

In Fig. 1 is shown the relationship between the ratio (A.C. resistance at 50 frequency)/(D.C. resistance) and the effective current density in the composite rod,

the effective current density being obtained by dividing the current by the equivalent area of 45·2 mm² as calculated in the foregoing.

These tests were made with values of the effective current density up to 27 amperes per mm², which

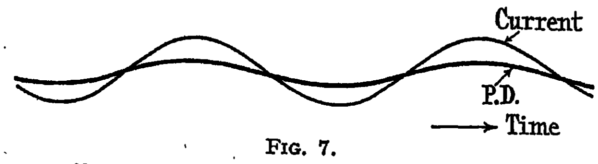

Fig. 7.
Note: The zero lines of the two waves are not coincident.

fully covers the range concerned in the starting conditions of squirrel-cage motors. Usually the normal full-load current density in practice is about 6 to 7 amperes per mm². During the starting period, however, the current density will be many times greater than the

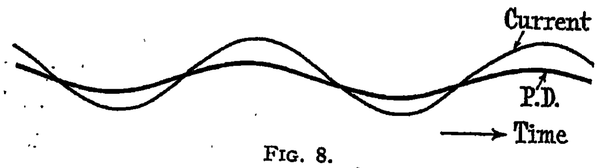

Fig. 8.
Note: The zero lines of the two waves are not coincident.

normal full-load value, and hence it is necessary that the tests should be made over a sufficiently wide range to cover the maximum current density likely to be obtained.

Reference to Fig. 1 shows that the effective resistance

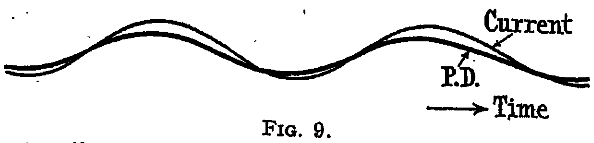

Fig. 9.
Note: The zero lines of the two waves are not coincident.

with alternating current at 50 frequency *decreases* slightly with the current density, the average value of the effective resistance being about 3 times the resistance as measured with direct current.

In Figs. 2, 3 and 4 are given the oscillograms of the

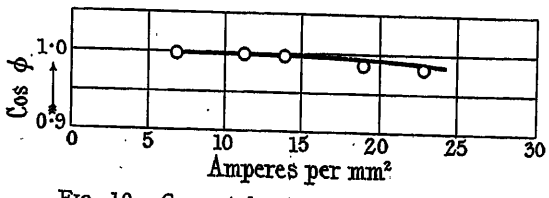

Fig. 10.—Current density in composite rod.

P.D. and current waves for current densities of 17·6, 22·1 and 26·6 amperes per mm² respectively. From these oscillograms the curve of Fig. 5 has been deduced, showing the power factor as a function of the current density, and it will be seen that the average value of the power factor in this case is about 0·987.

(ii) *Area of the outer copper skin* = 20·9 *mm*².—The total effective area of the composite rod in this case was therefore 55·8 mm², so that the ratio (Area of outer copper skin)/(Total effective area of composite rod) is 0·375.

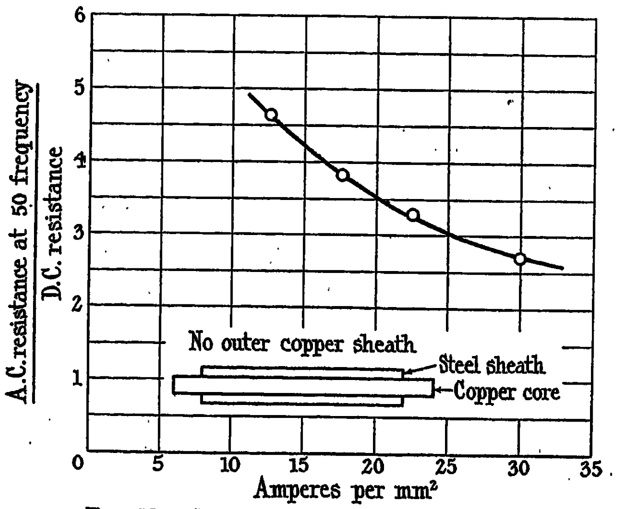

Fig. 11.—Current density in composite rod.

In Fig. 6 is shown the relationship between the ratio (A.C. resistance at 50 frequency)/(D.C. resistance) and the effective current density in the composite rod.

Fig. 12.
Note: The zero lines of the two waves are not coincident.

It will be seen that in this case the effective resistance *increases* slightly with the current density, the average value of the effective resistance for the range tested

Fig. 13.
Note: The zero lines of the two waves are not coincident.

being about 2·5 times the resistance as measured with direct current.

In Figs. 7, 8 and 9 are given the oscillograms showing the P.D. and current waves for current densities of 13·9, 19·0 and 22·9 amperes per mm² respectively. From these oscillograms the curve of Fig. 10 has been deduced showing the power factor of the composite

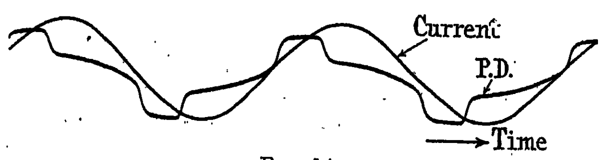

Fig. 14.
Note: The zero lines of the two waves are not coincident.

rod as a function of the current density, and it will be seen that the power factor for current densities up to about 15 amperes per mm^2 is very close to unity.

(iii) *No outer skin used.*—The composite rod comprising merely a central copper rod and a steel sheath corresponds to the proposal made by Elihu Thomson, to which reference has been made in the foregoing.

In order to ascertain for comparative purposes what the characteristics of this type of composite conductor are, tests were made with the composite rod detailed in the foregoing but with the outer copper skin removed.

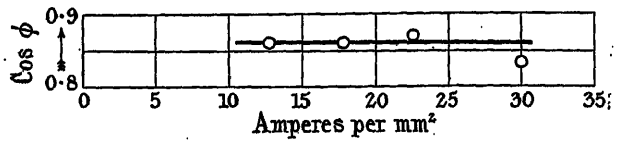

FIG. 15.—Current density in composite rod.

In Fig. 11 is shown the relationship between the ratio (A.C. resistance at 50 frequency)/(D.C. resistance) and the effective current density in the composite rod. It will be seen from Fig. 11 that the resistance decreases to a very marked degree with an increase of current density. That is to say, the rod has to some extent a negative resistance characteristic, which may result in an unstable condition so that the current may increase to an unduly large value.

In Figs. 12, 13 and 14 are shown the oscillograms for the P.D. and current waves for current densities of 17·75, 22·6 and 30 amperes per mm^2. From these oscillograms the curve of Fig. 15 has been deduced

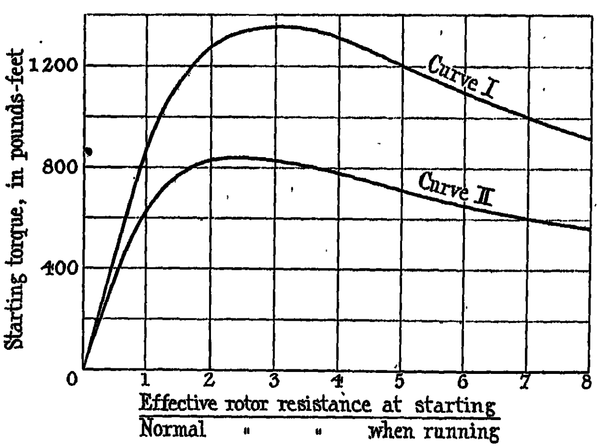

FIG. 16.

showing the relationship between the power factor of the composite rod and the current density, and it will be seen that the average value of the power factor in this case is about 0·865. This is a very low value and appears to the author to be one of the chief reasons why the use of such composite conductors (that is, without any outer copper skin) has not been found satisfactory.

In order to show the great significance of the power factor on the starting characteristics of the motor, the curves given in Fig. 16 have been calculated for the case of the motor for which the specification is given later in this paper. These curves show the relationship between the starting torque and the ratio (Effective rotor resistance at starting)/(Normal rotor resistance when running). Curve I refers to the case in which the increased rotor resistance at starting is obtained by means of conductors which have unity power factor, and Curve II refers to the case in which the increased rotor resistance at starting is obtained by means of conductors having a power factor of 0·86. It will be seen that for a given effective rotor resistance at starting the starting torque when the power factor is 0·86 is not much more than one-half the torque when the power factor of the resistance is unity. This shows in a very striking way the importance of obtaining the increase of the starting resistance at as high a power factor as possible.

The composite conductors with an outer copper skin have a further advantage over composite conductors without an outer copper skin, in that the power factor of the former when the rotor is running at normal speed will be considerably greater than the power factor of the conductors which have merely a steel sheath. The reason for this is that a large proportion of the current can flow through the outer copper skin when such is provided and, of course, in so far as the outer copper skin is concerned, the steel sheath has no effect on its inductance.

A further important deduction which can be made from Curve I of Fig. 16 is that the maximum starting torque obtainable by increasing the rotor resistance is reached when the increased rotor resistance is only about three times the normal running resistance.

TESTS B.

DETERMINATION OF THE INFLUENCE OF THE THICKNESS OF THE STEEL SHEATH ON THE CHARACTERISTICS OF THE COMPOSITE ROD.

In order to ascertain the effect of the influence of the thickness of the steel sheath on the characteristics

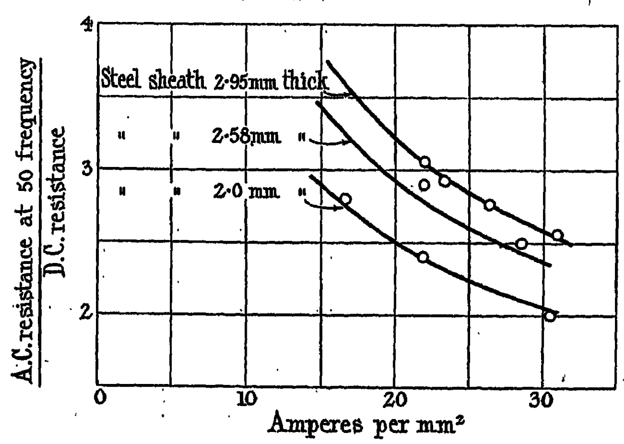

FIG. 17.—Current density in composite rod.

of the composite rod, tests were made with three rods, each having a different thickness of steel sheath. The

data of these rods and the results obtained from the tests are as follows :—

Composite Rod " A."

Thickness of steel sheath	2 mm
Diameter of central copper rod	6·1 mm
Area of central copper rod	29·4 mm^2
Radial thickness of steel sheath	2 mm
Length of steel sheath	20·2 cm
Effective cross-sectional area of steel sheath reduced to conductivity of copper ..	4·75 mm^2
Area of outer copper skin	6·30 mm^2
Total effective area of composite rod ..	40·45 mm^2

$$\frac{\text{Area of outer copper skin}}{\text{Total effective area of composite rod}} = 0{\cdot}155.$$

In Fig. 17 the results of the resistance tests on this rod are plotted as the lowest of the three curves there

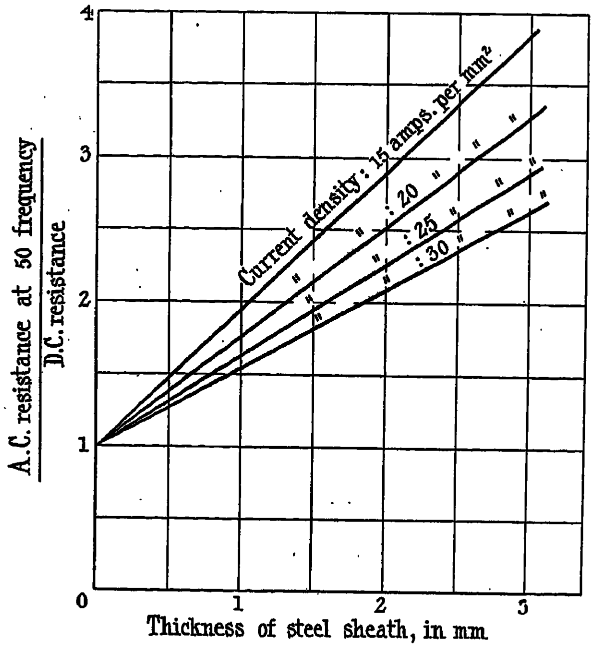

FIG. 18.

given. This curve shows the relationship between the current density in the rod and the ratio (A.C. resistance at 50 frequency)/(D.C. resistance).

Composite Rod " B." Thickness of steel sheath 2·58 mm.

Diameter of central copper rod	6·3 mm
Area of central copper rod	31·5 mm^2
Radial thickness of steel sheath	2·58 mm
Length of steel sheath	20·2 cm
Effective cross-sectional area of steel sheath reduced to conductivity of copper ..	6·63 mm^2
Area of outer copper skin	5·08 mm^2
Total effective area of composite rod ..	43·21 mm^2

$$\frac{\text{Area of outer copper skin}}{\text{Total effective area of composite rod}} = 0{\cdot}118.$$

In Fig. 17 the results of the resistance tests on this rod are given in the middle curve.

Composite Rod " C." Thickness of steel sheath 2·95 mm.

Diameter of central copper rod	5·9 mm
Area of central copper rod	27·3 mm^2
Radial thickness of steel sheath	2·95 mm
Length of steel sheath	20·2 cm
Effective cross-sectional area of steel sheath reduced to conductivity of copper ..	7·63 mm^2
Area of outer copper skin	5·7 mm^2
Total effective area of composite rod ..	40·63 mm^2

$$\frac{\text{Area of outer copper skin}}{\text{Total effective area of composite rod}} = 0{\cdot}14.$$

In Fig. 17 the results of the resistance tests on this rod are given in the highest of the three curves.

From the results given in the three curves of Fig. 17 the relationship between the thickness of the steel sheath and the ratio (A.C. resistance at 50 frequency)/(D.C. resistance) has been deduced and plotted in Fig. 18. This relationship has been deduced for the following values of the current density, viz. 15, 20, 25 and 30 amperes per mm^2 respectively. It is interesting to note in Fig. 18 that the a.c. resistance of the composite rod increases proportionally to the thickness of the steel sheath.

TEST-RESULTS OBTAINED FROM A SQUIRREL-CAGE ROTOR BUILT WITH COMPOSITE CONDUCTORS IN ACCORDANCE WITH THE AUTHOR'S PROPOSALS.

In order to obtain some practical test data as to the extent to which the results detailed in the foregoing could be usefully applied in the actual construction of a squirrel-cage rotor with high starting torque, Messrs.

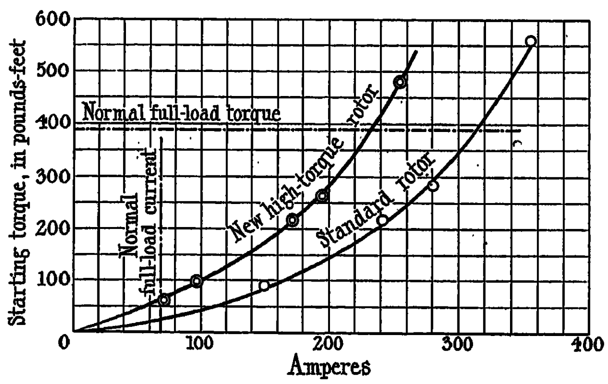

FIG. 19.—Starting-torque curves.

J. H. Holmes and Co., Ltd., in collaboration with the author, built a sample squirrel-cage rotor and tested it in a standard stator. The test data so obtained are given in the form of a series of curves (see Figs. 19 to 25).

A standard squirrel-cage rotor was then tested under the same conditions and with the same stator, the test data so obtained being also shown in Figs. 19 to 25. Each test-point obtained with the author's new high-torque rotor is shown in Figs. 19 to 25 by means of concentric circles, whereas each test-point obtained with the standard rotor is shown by a single circle.

Standard motor.—The specification of the standard motor used for the tests is as follows: 57 b.h.p.,

440 volts, 40 frequency, 6 poles, synchronous speed 800 r.p.m.

Stator :—72 semi-enclosed slots, 4 slots per pole per phase. Each slot contains 5 conductors of 0·29 in. × 0·18 in. compressed stranded copper arranged for star connection. The winding is the two-range or concentric type.

Rotor :—75 conductors, each 0·50 in. × 0·18 in.
Length of rotor bars, each 15·4 in.
Full-load current per bar, 360 amperes.
Short-circuit current per bar, 2 800 amperes.
Rotor core diameter, 13·44 in.
Rotor core length, 11·4 in.
Section of each end-ring, 0·30 square inch.

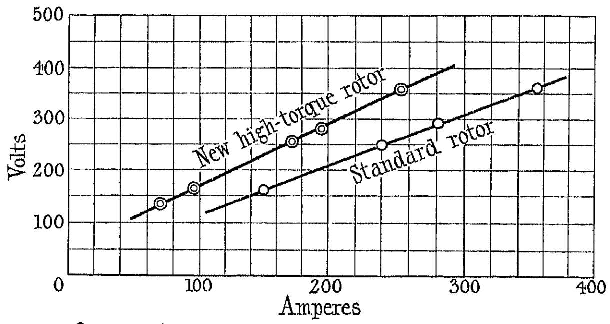

FIG. 20.—Short-circuit tests.

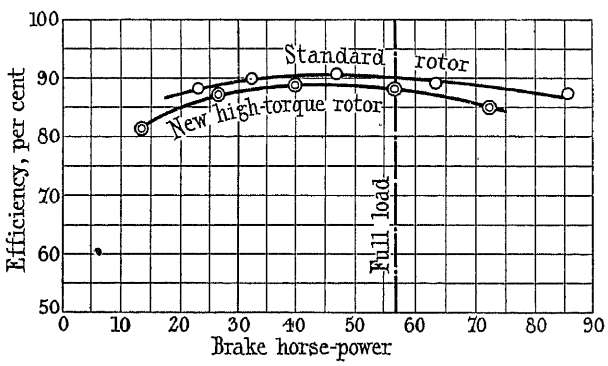

FIG. 21.—Efficiency curves.

New high-torque rotor with composite conductors.—60 circular semi-enclosed slots.

Each conductor is built up as follows (see Fig. 26) :

Diameter of central copper rod ..	..	0·236 in.
Internal diameter of steel sheath	..	0·251 in.
External diameter of steel sheath	..	0·485 in.
Thickness of outer copper skin	..	0·010 in.

The length of the steel sheath and the outer copper skin is 12 inches. The central copper rod was brought into good electrical contact with the steel sheath and the outer copper skin at each end. Each end-ring is of 0·90 square inch sectional area.

It will be observed that the diameter of the central copper rod is appreciably less than the internal diameter of the steel sheath. This was due to irregularities in the bore of the steel tube, which made it impossible to insert a copper rod of diameter larger than 0·236 inch. If the bore of the steel tube could be obtained dead true, it would be possible to avoid the waste space inside the steel tube (see Fig. 26) and thus obtain a composite rod of lower resistance. In this way the efficiency of the motor would be improved without impairing the starting conditions.

It was not considered desirable to punch more than 60 slots in the rotor for the composite bars, since this

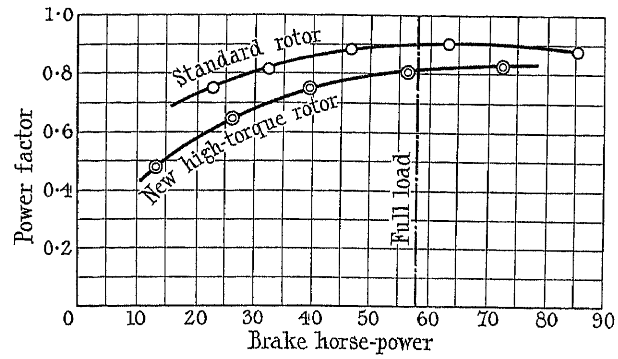

FIG. 22.—Power factor curves.

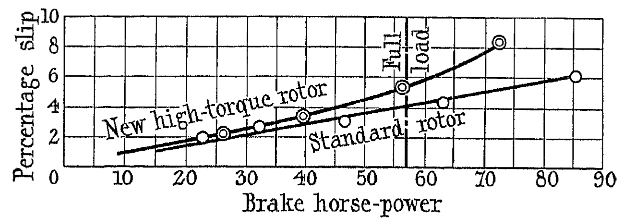

FIG. 23.—Percentage-slip curves.

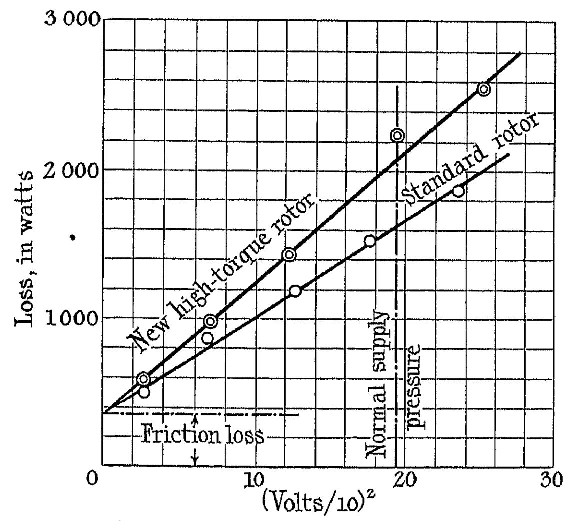

FIG. 24.—Core and friction losses.

would render the minimum section of the teeth too small for mechanical strength.

The relative performances of the new type of rotor and the standard rotor are clearly shown in Figs. 19 to 25.

The striking improvement in the starting conditions when the author's new high-torque rotor is used may be deduced from the curves of Figs. 19 and 20. For instance, to obtain the full-load torque at starting, with the author's new type of rotor, a current of

230 amperes is necessary (Fig. 19), and the applied voltage at the stator terminals will be 320 volts (Fig. 20).

If an auto-transformer is used for starting, the line current will be

$$\frac{320}{440} \times 230 = 167 \text{ amperes.}$$

Since the normal full-load current is 68 amperes, the full-load starting torque is obtained with a line current of only 2·45 times the full-load current.

If a similar calculation is carried out for the standard

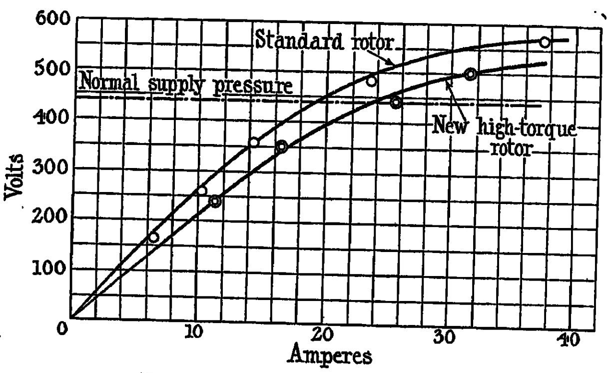

FIG. 25.—Magnetization curves.

rotor it will be seen that, in order to obtain full-load starting torque, the line current must be 3·37 times the full-load current.

As regards the efficiency, reference to Fig. 21 shows that the efficiency of the new type of rotor is slightly lower than that of the standard rotor. This is largely

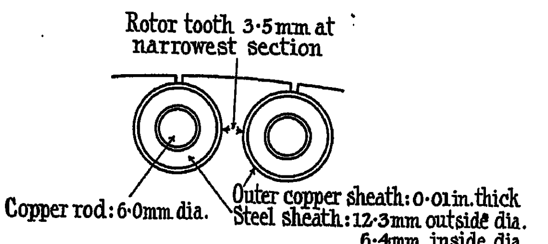

FIG. 26.—Showing the composite conductors in the new high-torque rotor.

No. of rotor slots = 60
Rotor diameter = 34·2 cm.
Air-gap = 0·75 mm.

due to the fact that the central copper rods of the composite conductors do not quite fill up all the space inside the steel sheaths, as was pointed out in the earlier part of the paper. This can be obviated in future and the efficiency at full load thus brought practically equal to that of the standard rotor.

APPENDIX.

Reduction of a Squirrel-Cage Winding to an Equivalent Winding having the Same Number of Phases and the Same Number of Turns per Phase as the Stator Winding.

A squirrel-cage winding is a polyphase winding of m_2 phases, where $m_2 = Z_2/p$, Z_2 being the total number of rotor bars and p the number of pairs of poles.

A squirrel-cage winding contains only one bar per phase, so that the number of turns per phase is $w_2 = \frac{1}{2}$.

Let r_r = resistance of the segment of one end-ring between two rotor bars (that is, the resistance of the segment A B in Fig. 27).

x_r = reactance of the segment of one end-ring between two rotor bars for a frequency equal to the stator supply frequency.

r_b = resistance of one rotor bar.

x_b = reactance of one rotor bar for a frequency equal to the stator supply frequency.

Then the effective resistance of one rotor bar plus the two end-ring segments is

$$r_2 = r_b + \frac{2r_r}{[2 \sin (\pi/m_2)]^2}$$

The reactance of one rotor bar plus the two end-ring segments is

$$x_2 = x_b + \frac{2x_r}{[2 \sin (\pi/m_2)]^2}$$

The actual squirrel-cage winding containing m_2 phases and w_2 turns per phase is equivalent to a winding

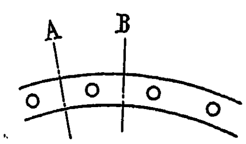

FIG. 27.

having m_1 phases and w_1 turns per phase and of which the resistance per phase is

$$r_2' = r_2 \frac{m_1(w_1 f_1)^2}{m_2(w_2 f_2)^2} = \frac{4m_1(w_1 f_1)^2}{Z_2} pr_2$$

where f_1 = winding factor of the m_1 phase winding,
f_2 = winding factor of the m_2 phase winding.

Since the squirrel-cage winding comprises only one bar per phase, the winding factor for such a winding is always equal to unity. As already stated, $w_2 = \frac{1}{2}$.

Similarly the reactance of the m_1 phase winding which is equivalent to the actual squirrel-cage winding is

$$x_2' = x_2 \frac{m_1(w_1 f_1)^2}{m_2(w_2 f_2)^2} = \frac{4m_1(w_1 f_1)^2}{Z_2} px_2$$

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Discussion before the Sheffield Sub-Centre, at Sheffield, 17 December, 1924.

Mr. D. B. Hoseason: The author points out the advantages of the squirrel-cage motor as compared with all other types of machines, and his proposal is intended to overcome the great objection to these machines in the matter of starting performance. It is well known that the standard squirrel-cage induction motor takes a high starting kVA per unit of starting torque developed, and although the author has termed his machine "a squirrel-cage induction motor with high starting torque" it would have been more effective to have called it a "squirrel-cage induction motor taking a low starting current." In my opinion there is a demand for a squirrel-cage induction motor which will permit the starting gear to be simplified. Only a few applications can be started by means of star-delta starting alone and it is usually necessary to employ either an auto-transformer starter or a star-delta starter with a centrifugal clutch. The star-delta starter and clutch is more expensive than the auto-transformer starter and it is generally the auto-transformer starter which is installed. This operates on about its 75 per cent tapping, and may cost as much as 33 per cent of the total cost of the installation; it has in all probability only half the life of the motor and, in addition, it is often a constant source of trouble to the maintenance engineer. It is worth while to examine the various methods which have been put forward in the past to improve the starting characteristics of squirrel-cage motors without appreciably affecting their normal running performance. Two of these mentioned by the author are the iron conductor and the copper-core steel-sheath conductor proposed by Elihu Thomson. There have also been a number of other patents generally on the lines of these two. In almost every instance the main principle of operation has been the equivalent of a high-resistance, low-reactance circuit in parallel with a high-reactance, low-resistance circuit in the rotor of the machine. At standstill with full line frequency being generated in the rotor the high-reactance, low-resistance circuit will pass very little current and give negligible torque, while the high-resistance, low-reactance circuit will pass appreciable current and give fairly high torque such as would be supplied by a slip-ring motor with a resistance inserted in the rotor circuit. At full speed the frequency in the rotor falls and the low-resistance circuit now has a much lower impedance than the high resistance circuit and carries the greater portion of the current. This low resistance would result in about the same slip on full load as a standard squirrel-cage motor. The reason for the comparative failure of the various methods put forward in the past is that no proper control over the ratios and values of the resistance and reactance of the two equivalent circuits is possible with the mechanical construction employed in the various cases. It is obvious that to obtain the fullest control and the best adjustment of these the two circuits should be completely separated. This is obtained in what has been called the double-wound squirrel-cage rotor. In this there are two distinct windings, an outer squirrel cage having a high resistance and low reactance, and an inner squirrel cage having a high reactance and low resistance. The values of reactance and resistance in each case can be adjusted to give the best possible performance. In the summary to the paper, the author says: "When alternating current flows through the compound conductor the portion passing through the central copper core produces in the steel sleeve a magnetic flux which induces a back E.M.F. tending to choke the current out of the core. The result is that the current will flow chiefly through the high-resistance copper skin outside the steel sleeve." It is suggested then that the proposals contained in the paper are essentially another variation of the double-circuit method, and furthermore that while this latest device may be a distinct improvement on the iron conductor or the composite conductor of Thomson, it is still inferior to the motor with two separate windings on the rotor. In fact it is a step back from the double-wound rotor machine. That this is the case is borne out by the fact that double-wound rotor machines can be designed and built to have far better starting and running characteristics than those of the 57-h.p. motor given in the paper.

Mr. G. H. Fletcher: The idea of utilizing the "skin effect" of conductors has been exploited for many years by design engineers, especially in connection with squirrel-cage motors. The majority of induction motor designers have been lured by the apparent possibilities, but my own investigations in this field, and consideration of other investigations which have been made from time to time, have resulted in a rather sceptical frame of mind, and the test-results given in the paper have destroyed the last vestige of my faith in the idea. Before referring to the general analysis of the test-results of the sample induction motor—which are, after all, the most important points—I wish to point out that these results, while showing the standard motor in a very favoured light as compared with the motor built up with composite bars, are hardly fair to the standard motor, owing to the fact that while the slip of the new rotor is 5½ per cent at full load the slip of the standard rotor is given as only 4·1 per cent. If the slip of the standard motor had been the same at full load as that of the new motor, the starting torque per kVA input would not have been much inferior. On comparing the efficiency and power factor of the standard motor against the power factor and efficiency of the motor with the new rotor, it will be seen that for a full-load current of 69·5 ampères the output of the standard motor is 57 h.p., whereas for the new type of rotor the output is actually less than 48 h.p. for the same total losses. This, of course, is a very serious matter because of the increase in weight and cost per h.p. Quite apart from their effect on the size of the motor, however, the reduced power factor and efficiency are quite serious in themselves, from the point of view of current consumption. A careful analysis will show that the inferior characteristics are not accidental but are inherent in the new rotor winding.

The power factor is reduced, partly due to the increased magnetizing current as shown in Fig. 25 (no doubt on account of the reduced iron section of the rotor teeth), but largely due to the increased leakage in the rotor bar, that is, the leakage flux which passes round the steel tubes surrounding the centre rod. So far as I can gather from the paper the detail tests of the composite bar have been made with the bar unsurrounded by iron. This condition, of course, is different from that under which the composite bar is actually used. Naturally, if a composite bar is tested in air the inductance of the outer copper section would be very much lower than that of the inner rod. When the composite bar is enclosed, or partially enclosed, in an iron core, the conditions are very different, the outer section itself then being inductive. This no doubt explains why the promising tests shown in the first part of the paper do not materialize when applied to an actual motor. The reduced efficiency is apparently due to an increase of 30 per cent in iron loss and an increase of 26 per cent in primary copper loss due to the increased primary current and 33 per cent increase in secondary copper loss. This latter loss, however, is useful in so far as it increases the starting torque of the motor. There are many important practical considerations such as cost and reliability, and it is quite certain that such a rotor must be more expensive than the standard rotor wound with copper bars and copper rings, and is more dependent upon efficient workmanship for reliable operation. As an alternative to the author's suggestion I would propose to increase the rotor resistance of the standard motor and thereby increase the slip from 4·1 per cent to 6 per cent. It is well known that the starting torque of an induction motor varies approximately in proportion to the full-load slip. In other words, if one were to take the standard motor as described in the text and increase the slip from 4·1 per cent to 6 per cent the starting torque would be increased proportionately. The kVA necessary to start this motor against full-load torque would be rather less than in the case of the high-torque motor. In other words, by the use of a suitable auto-transformer the current required to start would be approximately 165 amperes and, therefore, this motor would be at least as good as the rotor wound with composite bars from the point of view of starting, and on every other point the results would be very much superior. In Table A I give figures based on the figures given in the text for motors fitted with such rotors.

TABLE A.

	Rotor with composite bars	Standard rotor with 6 % slip
Output	48 h.p.	56 h.p.
Current to start against 57 h.p. load..	174 amps.	165 amps.
Power factor at start ..	0·42	0·48
Full-load power factor at 57 h.p.	0·81	0·90
Full-load efficiency at 57 h.p.	87·5 %	88·5 %
Maximum output	115 h.p.	155 h.p.
Stator current at rated output	78·2 amps.	69·5 amps.

In conclusion I would suggest that the new type of rotor might be considerably improved if the outer copper sheath were omitted altogether, the composite bars being composed simply of the inner copper core and the iron sheet. In this case the current would pass along near the surface of the steel tube, which, having a higher resistance than copper, would provide a path of higher resistance and therefore an increased starting torque. Even then it is doubtful if the results would be so much better than the ordinary standard method as to justify the increased complications.

Mr. E. A. Binney: Anyone familiar with the unfavourable position of the squirrel-cage motor in this country as compared with the United States must feel that a more lenient attitude towards this very useful motor should be taken by the power supply undertakings in this country. It is not reasonable to expect that all the advance towards assisting the more general application of the squirrel-cage motor should be made by the designer. At the same time, any step towards producing a squirrel-cage motor more favourable to the requirements of the power supplier should be encouraged. Various attempts to do this have been made in the past and the present paper should at least stimulate further effort along similar lines. At first glance the test-results on the composite bar lead one to expect very much better results than those shown by his test data on the experimental motor. The author shows that with his composite bar, presumably not assembled in a rotor slot, the current will flow with practically no lag, whereas the bar having no outer sheath shows a decided current lag. He deduces from this that, quite apart from other considerations, a material improvement in starting torque is to be expected. However, once the bar is surrounded by iron, as it is when assembled in the slot, this favourable condition disappears so that this factor would hardly enter into whatever improvement he finally obtains. The effect of the composite-bar construction on the effective resistance when currents at full frequency are carried, is an encouraging feature of both types of bar investigated, since it would appear that a very considerable increase in the rotor resistance at standstill could thereby be obtained without increasing the slip when operating at full speed. There appears to be no advantage in the author's additional copper sheath in this respect. However, unless the tests were carried out with the bars assembled in slots the results may be misleading. Unfortunately, the experimental tests indicate that the sample motor works with a higher slip at full load, which makes a direct comparison with the standard motor impossible. The power factor readings obtained with locked rotor would have given some clue to the actual increase in rotor resistance realized. It is unfortunate that the two motors compared were not identical in all respects with the exception of the rotor bars. The number of slots in the standard rotor is greater, and this would affect the results. The standard motor appears to have rectangu-

lar bars ; this is a more economical shape than the round bar adopted for the experimental motor. The latter has very heavy end-rings as compared with the standard motor, which alters the ratio of ring and bar resistance in the two cases. These factors all tend to make fair comparison of the two motors difficult to anyone not well versed in the design of induction motors. It would appear that the composite type of bar causes a great increase in the rotor slot leakage, which is reflected in the greatly reduced overload capacity of the motor. This is an unfavourable feature and in my opinion detracts materially from any advantage gained in the starting performance. Unless the increase in effective rotor resistance during starting can be obtained without materially increasing the leakage, it does not seem that really outstanding results are likely to be obtained.

Mr. H. W. Walker : Previous speakers have referred to the restriction by various supply authorities of the use of moderately large squirrel-cage motors. Whilst this is generally true, I know of a certain municipal power station which uses 125-h.p. squirrel-cage motors to drive the rotary pumps on the condensers. The author's high-torque rotor, in my opinion, may not come into general commercial use so as to displace entirely the present simple and robust type of squirrel-cage rotor. With a little improvement they will mostly be used for directly driving high-speed rotary pumps and blowers, etc., which require abnormal torque to accelerate.

Mr. H. E. Yerbury : Every engineer is, I think, agreed that if squirrel-cage motors could be designed for high starting torque and low starting current a big field would be open for their use. The author rightly says that for simplicity and robustness they cannot be equalled. The tests of his 57-h.p. motor show, unfortunately, that power factor and efficiency are lower than on an ordinary type of motor. These are serious drawbacks as they are evident throughout the full range of the tests and are shown clearly in the curves. Full starting torque was attained on the test motor with a line current of 2·45 times the full-load current. It therefore appears necessary to provide an auto-starter which incidentally is nearly double the price of a secondary starter for a slip-ring motor. It would be unfair to expect a general electricity supply department to provide plant and cables greatly in excess of the full load connected ; hence it is customary to specify that a motor should not take more than about $1\frac{1}{4}$ times full-load current at starting. On a power supply or railway and tramway supply only, it would not be deemed serious and would be scarcely noticeable if the supply voltage fluctuated from 5 to 10 per cent. Whether the effects of a large starting current are serious or not is of course dependent on the location of the motor on the supply network, and an intermittent diminution of voltage on a lighting circuit is most undesirable and in fact prohibitory. In short, low starting current is of more importance to a supply department than high starting torque, the application of which has, I think, only a limited field. The commercial aspect cannot be ignored, and it would be interesting to learn the relative cost of the author's new machine. A slip-ring motor of, say, 55 h.p., costs about 25 per cent more than a squirrel-cage motor, but until the author goes further and designs a motor which will reduce the starting current to, say, $1\frac{1}{2}$ times full-load current, the consumer will still be burdened with an extraneous device to effect this desired result, and this starter will cost twice as much as for a slip-ring motor. Finally, therefore, there is not more than 10 per cent difference in capital costs, but the maintenance costs are obviously lower on a squirrel-cage motor. As with the author's motor an auto-transformer has to be inserted to reduce the current, is not the object of his new design thereby partly defeated ? Further, for what purposes, apart from lift and crane motors, does he think his special motor is required, and does he not think that there is more likelihood of the insulation deteriorating, and that any type of motor would have a shorter life if the full or nearly full voltage of the supply were impressed upon it at each starting period ?

Prof. E. W. Marchant (*communicated*) : The ingenious device of building a squirrel-cage rotor for an induction motor with composite rods having a copper core surrounded by an iron sheath, which in turn is covered by a thin outer copper sheath (thus increasing the effective resistance of the rotor bars for the relatively high-frequency currents which are induced when starting the motor), is an important improvement in the design of induction motors. The circuit of a rotor constructed with bars of this character has a much higher power factor than one made with steel-covered copper bars such as were described by Elihu Thomson. This has been shown clearly by Dr. Wall's experiments, and the importance of this result is demonstrated very clearly in Fig. 16. With a ratio of effective rotor resistance at starting, to rotor resistance when running, of 3, the starting torque when the power factor of the rotor is unity is 1 350 lb.-ft., whereas with a power factor of 0·86 the starting torque is about 820 lb.-ft. It is interesting to note also that no gain in starting torque is obtained when the ratio of resistance at start to running resistance is greater than 3. The circle diagram shows that there must be a limit to the gain in starting torque obtained by increasing the rotor resistance, and the author's figure for the best ratio should be useful to designers. He has designed a motor which should be of great service where a robust motor with high starting torque is needed. It has all the advantages of the squirrel-cage motor in simplicity of construction, with a starting torque of the same order of magnitude as that obtained with the much more complicated, wound rotor. This result has been obtained at the expense of a relatively small loss in efficiency and power factor.

Dr. T. F. Wall (*in reply*) : In the course of the discussion, reference has been made to the double-wound rotor of Boucherot. This type of motor is, of course, subject to deficiencies of an exactly similar nature, viz. reduced efficiency and power factor, as are shown in the test-results given in the paper for the composite conductor rotor. The double-wound rotor has, however, the further disadvantages that its size and cost for a given output must obviously be considerably greater. I have given a fully worked out example of the performance of a Boucherot motor in *Engineering*, August 10, 1923.

The machine of which the test data are given in the present paper is the first of this size to be completed and tested. So far as I am aware these test data are the first yet published for a rotor built with composite conductors. It is therefore obvious that the results obtained are not submitted as giving the best possible performance of which motors built in accordance with this invention are capable. For example, the performance would have been appreciably improved if it had been possible to choose a larger number of rotor slots, as would have been the case if rectangular conductors had been employed. Such rectangular composite conductors would be practicable if the steel sheath were formed from rectangular "washers" stamped out of laminated iron and threaded on the central rectangular conductor, the whole being covered with the copper skin.

A further consideration as regards the field of application of this new type of rotor is that in many cases it would be feasible to use series starting resistances, instead of an auto-transformer, when it is necessary to reduce the starting current to a value still lower than that obtained by switching the motor directly on to the line. Series starting resistances provide the cheapest form of starting gear, and this item would be similar to the starting resistance of a wound rotor, with the exception, of course, that it would be connected in the stator circuit instead of in the rotor circuit.

In designing a standard line of these motors it would be possible to design machines that would have appreciably better starting characteristics than those of the experimental sample specified in the paper. It is, however, hoped that these results will form the basis from which further advances may be made.

Mr. Fletcher seems to me to have formed a gloomy opinion of the possibilities of this invention which is certainly not justified by any test-results given in the paper. If his pessimism is based on experience with the simple steel-sheathed conductor I can understand it. I consider, however, that the addition of the outer copper skin introduces an entirely new and beneficial factor in the design of composite conductors and brings them within the realm of practical application. Mr. Fletcher states that "for the same total losses" the new high-torque rotor will give less than 48 h.p. as compared with 57 h.p. by the standard rotor. He then proceeds to increase the rotor resistance of the standard motor by about 45 per cent, and draws up Table A in which the standard motor is allowed to have appreciably greater total losses than the new high-torque motor for the specified ratings. The data given in Mr. Fletcher's Table A are wrong in important respects. Increasing the slip of the standard rotor from 4·1 per cent to 6 per cent, i.e. by about 45 per cent, will raise the torque curve in Fig. 19 by a corresponding amount, but even then the torque curve is markedly below that of the rotor with composite bars, and the starting current at full-load torque is appreciably higher than that of the composite-bar rotor. In view of these facts, I consider Table A to be of no value as a criticism of the new high-torque rotor.

As regards the applicability of the tests on single isolated composite rods, there seems to be a misapprehension. The tests on the isolated composite rods give the inherent characteristics of these rods, and this information is the essential feature in considering the possibilities of such rods when used as rotor conductors. The comparison of the test-results for single isolated composite rods with outer copper skins and single isolated plain steel-sheathed copper rods is a perfectly legitimate one, and the great advantages shown by the former will be evident in test-results from rotors constructed respectively from these two types of composite conductors. There is, however, a further very important consideration to bear in mind, viz. that whereas the plain steel-sheathed copper rods will most seriously (and, I think, prohibitively) increase the slot leakage, the composite rods with outer copper skins will cause nothing like this increase in slot leakage, for the simple reason that the flux passing through the steel sheath will also cut the outer copper skin and is therefore not leakage, although it may give rise to a certain amount of eddy-current loss in the copper skin. This may, in fact, partly account for the slightly lower efficiency of the composite-rod rotor as shown in the test-results given in the paper. In view of the considerations already detailed and also in view of the test-results given in the paper, the suggestion that plain steel-sheathed copper rods would be preferable to the steel-sheathed copper rods with outer copper skins seems to me to be wholly unsupported either on logical or on experimental grounds.

Mr. Yerbury points out that the composite-bar rotor will draw more than 1½ times the full-load current from the line if switched directly on to the line at starting. This is quite true, but I think that the time has arrived when electric supply undertakings should relax their ruling that induction motors shall not take more than about 1½ times full-load current when starting. Designers should be met at least half-way in this respect and I submit that not to do so is putting difficulties in the designers' way which are largely unnecessary. There seems to be very little real justification for this severe restriction on the amount of starting current.

It is not expected that the cost of rotors with composite conductors will show up advantageously in all cases as compared with normal squirrel-cage rotors. Investigation shows, however, that there is a range of motors of medium output for which the cost of this new type of rotor will compare favourably both as regards slip-ring rotors and normal squirrel-cage rotors.

That there is a real and definite need for a satisfactory squirrel-cage induction motor with high starting torque is, I think, most conclusively proved by the fact that such a large number of electrical engineering firms in this country, on the Continent, and in the United States, have made such persistent efforts to solve the problem. That this is so is borne out by reference to the Patent Office records and to the technical Press.

I am not quite clear as to what Mr. Yerbury refers with regard to possible insulation troubles. It is not necessary to have any insulation in the rotor slots. As is so often the practice with normal squirrel-cage rotors, the conductors may be laid directly in the rotor slots.

I much appreciate the remarks of Prof. Marchant. I thank him for calling attention to some of the salient facts given in the paper, and for his appreciative view of the proposals on which the paper is based.

EFFICIENCY OF END CONNECTIONS, AND THE SHORT-PERIOD RATINGS OF LARGE-CURRENT SHUNTS.*

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[FROM THE NATIONAL PHYSICAL LABORATORY.]

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SUMMARY.

The efficiency of the end connections, which was discussed by a Committee of the British Engineering Standards Association when considering the standardization of shunt ends and switchboard connectors, has been investigated. The results show that with brass lugs the contact resistance is considerably higher than with copper, and also that with brass ends the pressure-drop across the two joints is of the order of 20 mV as compared with 75 mV across the shunt itself. With copper ends the voltage-drop is only 3 mV.

The temperature-rise of the resistance elements of shunts carrying overloads was investigated. The amount of overload which a shunt will carry during short periods before a given temperature excess is reached depends almost entirely on the heat capacity of the metal of which the shunt is composed, the effects of radiation and convection under these circumstances being negligible by comparison. Formulæ for the evaluation of short-period overloads were deduced from the dimensions of typical shunts for a given value of the temperature excess, and were checked by results obtained from actual overload tests.

INTRODUCTION.

In connection with the work of the Instrument Committee of the British Engineering Standards Association, it was considered desirable to investigate before they were definitely adopted for standard practice the proposed standard sizes for shunt ends and other apparatus used on or with switchgear.

Three shunts, designated A, B and C, were kindly lent by Messrs. Elliott Brothers, Ltd., and Messrs. Nalder Brothers and Thompson, Ltd. These all had the standard pressure-drop of 75 mV and were for normal maximum currents of 2 500, 3 000 and 5 000 amperes respectively.

In their general shape and design these three shunts were very similar, and the total cross-section of the metal in the resistance elements was proportional to the current to be carried, so that there is no reason to ascribe any variations in the behaviour of the end contacts to this factor.

The principal dimensions of these three shunts are given in Table 1, and in Fig. 1 they are shown drawn to the same scale. The 2 500-ampere shunt A was fitted with copper lugs, the other two shunts with brass.

The proposed standardizing of the dimensions related only to the size and spacing of the bolt holes; the thickness, overall width and length of the lug being left to the individual maker. In the three shunts tested the actual width, length and thickness were so dimensioned that small variations would probably not greatly affect the results.

For the purpose of the tests the shunts were connected with copper busbars of the same width as the lug, one on each side of the lugs. The thickness of each of the strips was ⅜ in. for the 2 500-ampere and 3 000-ampere shunts, and ½ in. for the 5 000-ampere shunt. Thus the sectional area of the copper connecting-pieces

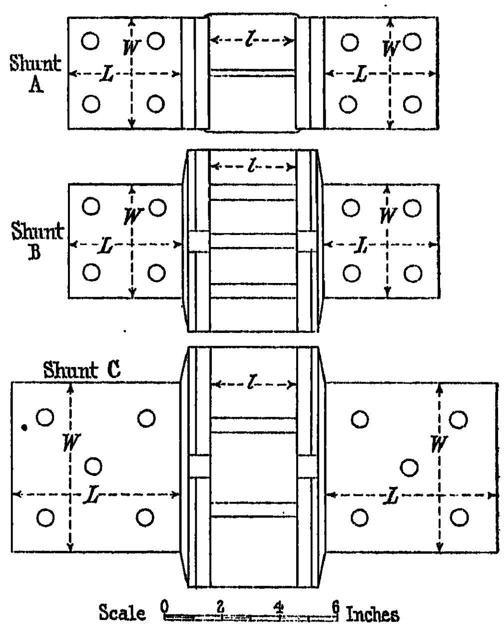

FIG. 1.

was 3 sq. in. for the two smaller shunts and 6 sq. in. for the 5 000-ampere shunt.

RESULTS OF TESTS.

As regards the number and arrangement of the bolt holes, previous work had indicated that an intermediate fifth bolt did not improve the contact, and this was again confirmed in the case of shunt C (Fig. 1). The fifth bolt hole would therefore appear to be unnecessary.

The question as to what constitutes an efficient joint for the purpose of a shunt is a matter of some doubt. The definition used by the authors in their previous

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work * was as follows: "An efficient joint is one in which the total resistance of the length comprising the joint is not greater than that of an equal length of the straight conductor," and this probably holds for all ordinary switchboard practice, though for a shunt it may be argued that a pressure-drop of 20 mV across the two joints is small in comparison with the drop across the shunt itself. For the present purpose, however, the authors have again adopted this definition.

The results for the three shunts are set out in Table 1. It will be noted that the efficiency of shunt A fitted with copper lugs is very good, the resistance of the joint being considerably less than that of an equivalent length of the straight (copper) conductor. On the other hand the efficiency of contact of the brass lugs is somewhat low, being of the order of 37 per cent.

It will be seen from the table that the copper lugs in the small shunt are thicker than the brass lugs for the larger shunts; thus the actual metallic resistance given in the table for this shunt is lower in proportion than that of the other shunts. The higher efficiency of the joints of shunt A as compared with B and C, however, arises only in a small measure from this cause. As will be seen from the values given for R_C, the contact resistance of copper to copper is very much less than that of copper to brass. This point has been noticed before, but has not yet been fully investigated.

The fact that the thermal conductivity of copper is at least 3 or 4 times as great as that of brass, although the effect of it is not apparent in the present connection, requires, however, to be noticed as being a factor of considerable practical importance, since better thermal conductivity of the parts involved will help materially in dissipating the localized heating which is developed at the place where the resistance elements are soldered into the shunt-ends.

* *Journal I.E.E.*, 1922, vol. 60, p. 892.

TABLE 1.

Shunt	Current	L	T_1	T_2	W	Voltage-drop (one joint) of overlap at full load	$R = R_M + R_C$	t	R_M	R_C	R_B	R_L	Joint efficiency, $100R_L/R$
	amps.	in.	in.	in.	in.	mV	microhms	°C.	microhms	microhms	microhms	microhms	
A (copper)	2 500	4	$1\frac{1}{4}$	$\frac{3}{4}$	4	1·48	0·59	62	0·42*	0·17	0·264	1·058	179
B (brass) .	3 000	4	$\frac{3}{4}$	$\frac{3}{4}$	4	8·04	2·68	41	0·82	1·86	0·245	0·980	36·5
C (brass) .	5 000	6	1	1	6	10·3	2·06	45	$0·61_2$	$1·44_8$	0·126	0·758	37·3

L = length of overlap.
T_1 = thickness of lug.
T_2 = thickness of the double busbar.
W = width of lug and busbar.
R = resistance of overlap.
t = temperature of overlap.
R_M = resistance of metal parts of overlap.
R_C = resistance of contact surface of overlap.
R_B = resistance of 1 in. of double busbar.
R_L = resistance of length L of double busbar.

Note.—In computing R_M the resistivity of the brass was taken as 3·0 microhms per inch cube with a temperature coefficient of 0·001 per deg. C., and the resistivity of the copper as 0·678 microhm per inch cube with a temperature coefficient of 0·004 per deg. C.

* The thickness of that portion of the busbar which formed the overlap was in this instance reduced to $\frac{11}{32}$ in.

SHORT-PERIOD OVERLOAD RATINGS OF SHUNTS.

The following investigations were carried out on the three shunts A, B and C, in which the pressure-drop at full load was 0·075 volt, and also on a 5 000-ampere shunt D, in which the pressure-drop was 0·2 volt at full load. The object of these investigations was to find how far shunts for heavy current could be overloaded for short periods without the temperature-rise becoming excessive and endangering the soldered joint or changing the resistance of the shunt.

In the case of a simple conductor the problem might be solved from a general knowledge of the heat-capacity and heat-emissivity characteristics of the conductor, but in the case of shunts the factors involved are too complex to permit of any general solution of the problem being arrived at on these lines, except under certain special circumstances to be discussed later. The general treatment of the problem which is applicable in the case of a simple conductor is possible only because certain simplifying assumptions can be made. It is permissible, for instance, to regard the conductor as thermally homogeneous so that when it is carrying current the heat generated will be uniformly distributed within the metal and uniformly dissipated to the surrounding medium, and not to any appreciable extent through or into the end connections. The surrounding medium may also be assumed to remain throughout at an approximately invariable temperature and not to be affected by the rising temperature of the heated body. Under these conditions, and assuming that over a limited range of temperature difference the heat is dissipated at a rate proportional to the temperature excess, the relation of temperature-rise to time will then be of the simple form

$$\theta = m\,(1 - \epsilon^{-t/\gamma}) \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where, for any given current,

θ = the temperature excess of the conductor above the surrounding air,
m = the final maximum temperature excess produced by the given current,
t = the time which has elapsed since the current was switched on,
γ = the time-constant of the conductor, i.e. the ratio of the heat capacity to the rate at which heat is lost to the surrounding medium for a unit temperature excess.

In a shunt, however, because of its more complicated structure, the conditions are substantially different. The heat developed by the current is carried off, not only by radiation and convection into the surrounding medium, but also, and to a very considerable extent, by direct conduction through and into the end pieces and connections to which the shunt is attached. The temperature of these end pieces rises both in consequence of the local effects of the current and of the heat that flows into them from the resistance element.

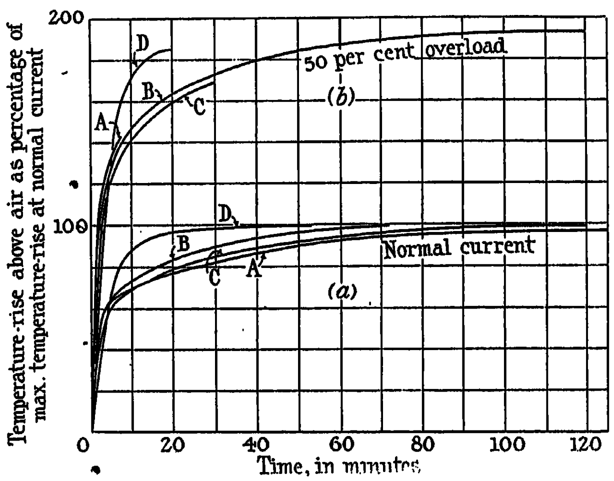

FIG. 2.—Comparison of temperature-rise of four shunts, (a) at normal rating and (b) at 50 per cent overload.

Where, however, the simple relation expressed by Equation (1) holds, the rise of temperature for any such simple conductor, at any given period after switching on the current, will in every case be in the same ratio to the final maximum value. Thus under two different conditions of loading for which the final maximum temperatures would be M_1 and M_2 respectively, the two corresponding values of the temperature excess at any time t_0 before the final temperature is attained would also be in the ratio of M_1 to M_2. In cases of this kind, therefore, the theoretical determination of the time that will elapse before the temperature excess reaches any prescribed value could easily be calculated if the thermal characteristics of the conductor were approximately known.

The extent to which the thermal behaviour of the resistance elements of a heavy-current shunt departs from this simple relation will be seen from Table 2, which gives in the case of the three shunts B, C and D the temperature excess (a) for normal loading, (b) for a 50 per cent overload, and (c) the ratio of these two sets of values taken at various intervals during the first portion of the heating curve. It will be seen that neither for the same shunt at different parts of the curve nor for different shunts at the same time-interval after switching on, is the ratio constant. The temperature-rise curves of these three shunts, together with that of shunt A, are also shown in Fig. 2, in each case as a percentage of the final temperature. The rapid rise of temperature in shunt D is no doubt chiefly due to the fact that though larger and heavier than the other three shunts the voltage-drop is 0·2, whereas in the others it is 0·075.

TABLE 2.

Shunt	Time	θ_a (Temperature-rise with normal rating)	θ_{50} (Temperature-rise with 50% overload)	Ratio θ_a/θ_{50}
	mins.	deg. C.	deg. C.	
B	2·5	50·5	99·5	0·508
	5	61·5	123	0·500
	7·5	68·5	134·5	0·508
	10	72·5	141·5	0·512
	15	77·5	151	0·513
	20	81·3	158·7	0·512
	30	86·5	169·3	0·512
	40	91·3	177	0·516
C	2·5	47·0	97	0·485
	5	60	123·5	0·485
	7·5	66	140·5	0·469
	10	69·5	143	0·486
	15	75	154·5	0·485
	20	79	161·5	0·490
	30	85	171·5	0·495
	40	89·4	179	0·50
	60	95	187·5	0·56
D	2·5	35·5	75·5	0·470
	5	62	128·5	0·483
	7·5	78·5	156	0·503
	10	86·5	169	0·510
	15	90·0	175	0·514
	20	95	181	0·524
	30	96	182	0·527

An approximate indication of the length of time during which an overload is permissible is given in Fig. 3, which shows the rise of temperature in shunt A with normal current, and with 50 per cent, 100 per cent and 200 per cent overload respectively. The heating of the positive and negative ends for normal current and 50 per cent overload is also given. It will be seen that with 200 per cent overload a temperature excess of 200 deg. C. in this instance is reached in about 1 minute after the current is switched on, but with a 100 per cent overload this temperature is not reached until the current has been flowing for about 6 minutes. The ends of shunt A were of copper and the positive end during the first 10 minutes did not attain to more than 20 per cent of the temperature-rise of the hottest of the

resistance strips, to the behaviour of which the temperature curves in all cases refer, except where otherwise stated. In B, a 3 000-ampère shunt with brass ends, the temperature-rise of the ends was relatively greater, and during the first 10 minutes attained to about 50 per cent of the temperature of the hottest strip. This must have a very direct effect on the rate of temperature-rise of the resistance elements themselves,

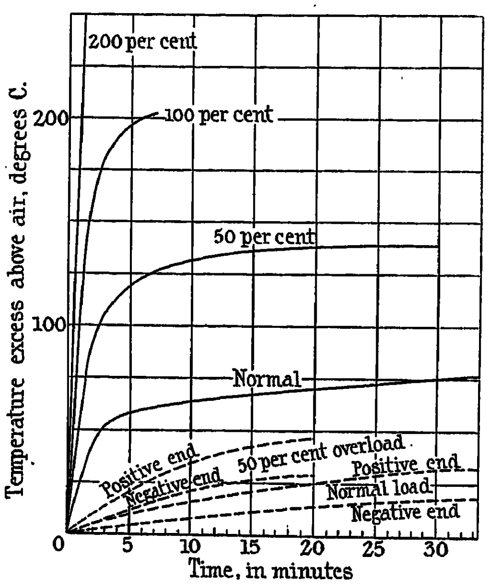

FIG. 3.—Temperature of resistance element and ends of a 2 500-ampere shunt with various overloads.

and it is probable that to this effect are chiefly to be attributed the differences in the character of the temperature-rise curves, especially during the first few minutes. These differences are well exemplified in Fig. 2, from which it will be seen that the time taken to reach a given temperature (the final maximum temperature for normal rating being in all cases approximately the same) may vary by as much as 100 per cent.

Where the maximum permissible temperature-rise is reached in a few seconds—this happens when the shunt carries a very heavy overload—the problem becomes amenable to a very simple method of treatment. During such periods very little of the heat developed will have time to escape, either by radiation and convection, or by conduction. For practical purposes it will therefore be sufficiently correct to assume that, for a very short period after switching on, the whole of the heat energy developed in the resistance elements goes to raise the temperature of the metal. The rate of temperature-rise will therefore depend entirely upon the voltage-drop and current on the one hand, and the mass, resistivity and specific heat of the metal on the other. If constant values are assumed for these quantities it is then possible to obtain a general formula.

Let it be assumed that the resistance elements are of manganin and that the mean resistivity $\rho = 42$ microhms per cm cube, the density $d = 8 \cdot 4$, the specific heat $s = 0 \cdot 50$ (in electrical measure), l = the length of the resistance element in cm, M = mass of the resistance elements in grammes, and R = resistance in ohms. Then, on the assumption that there is no escape of heat, the temperature-rise θ when a current I has been passing for t seconds is

$$\theta = \frac{RtI^2}{Ms}$$

If the voltage-drop is $0 \cdot 075$ when I', the normal rated current, is passing, then

$$R = 0 \cdot 075/I' = \rho l/A$$

and

$$M = dlA$$

A being the total cross-section of the resistance material.

We therefore have

$$\frac{I}{I'} = \frac{l}{0 \cdot 075}\sqrt{\left(\frac{\rho d s \theta}{t}\right)}$$

If we assume an initial temperature of 20° C. and that 200° C. is the maximum, then $\theta = 180$, and if, as is frequently the case, $l = 7 \cdot 5$ cm (approximately 3 in.) on substituting the numerical values given for ρ, d and s the formula reduces to

$$I/I' = 17 \cdot 8/\sqrt{t}$$

which is the overload factor; or

$$t = 317\left(\frac{I'}{I}\right)^2$$

which gives the time during which the overload current may be carried.

TABLE 3.

Ratio of overload to normal rated current	1·5	1·7	2·0	2·5	3·0	5·0	10
Time in seconds to attain 200° C. assuming that shunt							
(a) was previously cold	141	109	79	51	35	12·7	3·2
(b) had been running at normal current	78	61	44	28	20	7	1·7

But these formulæ are based on the assumption that, when the overload is switched on, the shunt had previously been carrying no current. If the shunt for some time previously has been carrying the maximum rated current and under these conditions is then suddenly called upon to carry an overload, the temperature-rise can no longer be taken as 180 deg. C. but as the

difference between 200° C. and the temperature which the shunt attains at full-load current. If this latter be taken as approximately 100° C., θ becomes 100 deg. C. and the formulae become

$$\frac{I}{I'} = \frac{13 \cdot 3}{\sqrt{t}}$$

or

$$t = 176\left(\frac{I'}{I}\right)^2$$

With this assumption a series of short-time ratings corresponding to various overloads was calculated by the use of the formula and is shown in Table 3.

This would indicate that if the overload period does not exceed 1 minute an overload of 130 per cent above the normal rating current would be permissible if the shunt started cold, but that an overload of 70 per cent could be allowed if the shunt had previously been running at full load. Reference to the curves for 200 per cent and 100 per cent overload in Fig. 3 will show that this is approximately correct.

Note.—In all the shunts tested the temperature-rise for normal maximum continuous loading was of the order of 100 deg. C., and in discussing the effect of overloads and the application of the formula in the examples worked out the authors have considered a value of 200 deg. C. This latter figure is purely arbitrary and was taken as being rather below the melting-point of soft solder. It is not suggested that this or any and every type of resistance alloy that might be used could safely be raised to this temperature without permanent injury or change, or that this value should be adopted as standard practice.

DISCUSSION ON
"A NEW NETWORK THEOREM." *

Mr. A. Morris (*communicated*): Mr. Rosen's paper is of considerable general interest and of great practical utility to engineers and others who are concerned with electrical networks. The title of the paper indicates that the theorem is new; this, however, is not the case. Mr. George A. Campbell published it in perhaps an even more general form—in the *Bell System Technical Journal*, July 1922 (vol. 1, No. 1), in an article entitled "Direct Capacity Measurement." This article contains the following statement: "Generalizing, we have the following definition: The direct capacities of an electrical system with n given accessible terminals are defined as the $n(n-1)/2$ capacities which, connected between each pair of terminals, will be the exact equivalent of the system in its external reaction upon any other electrical system with which it is associated only by conductive connections through the accessible terminals." I quite believe that Mr. Rosen was without knowledge of Campbell's article when he submitted his paper for publication and that he has in fact worked out the theorem quite independently. The theorem is, however, of such importance, and would appear to be so little known, that its publication in the pages of the *Journal*, two years after its having been first enunciated, is probably fully warranted.

The following example of the use of the theorem applied to impedance operators will doubtless prove of interest. This example involves the use of the star to mesh and also the mesh (triangular) to star (three ray) transformations. The network concerned arises in connection with the localization of a certain class of dielectric fault occurring in electric cables.* Fig. A shows the magnitude of the impedance of each network-member, as well as its arrangement. PQSL and VUTL represent the separate conductors of the faulty cable circuit, which are joined together at the end L for the purpose of localization. ZQ and ZU represent the normal insulation resistances to earth of the conductors, whilst ZS and ZT represent the resistances of the "earth" faults existing at the points S and T respectively. PH and HW represent ratio arms, G a galvanometer, HZ an earthed battery and WV a resistance which can be adjusted until balance of the galvanometer is secured. The fault on the cable circuit is situated at a point x ohms from the end V of the conductor VUTL. The resistance of each conductor

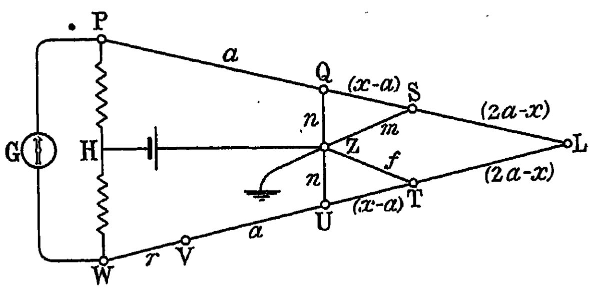

Fig. A.

* Paper by Mr. A. Rosen (see vol. 62, p. 916).

* A. Morris and R. M. Chamney: "Considerations relating to the Murray Loop Test," *Journal of the Institution of Post Office Electrical Engineers*, 1918 vol. 11, part 1; also H. T. Werren: "The Localization of Low Insulation Faults in Underground Cables," British Post Office Research Report No. 1672, November, 1922.

is $2a$ ohms, whilst the normal insulation resistance and the fault resistances are n, m and f ohms respectively. The magnitude of the adjustable resistance WV, when a balance has been secured, is r ohms.

In order to derive the condition for balance of the network by the usual methods, it would be necessary to solve a seven-row determinant. By the use of the theorem the equation for balance may be written down at once if the network is first simplified.

In the expressions about to be derived the following abbreviations will be used :—

(i) For $[m + f + 2(2a - x)]$ write $1/g$.
(ii) For $[a - x + 2mg(2a - x)]$ write $1/h$.
(iii) For $[a - x + 2fg(2a - x)]$ write $1/k$.
(iv) For $[mfg(h + k) + 1]$ write s.
(v) For $[mfg(h + k) + nh + 1]$ write t.
(vi) For $[mfg(h + k) + nk + 1]$ write u.
(vii) For $[mfghkn(u + t) + ut]$ write w.

The simplification is effected as follows :—

(*a*) Replace the two members SL, TL by the single member ST; whence ST $= 2(2a - x)$.

(*b*) Transform the triangular mesh ZST into the three-ray star YZ, YS, YT; whence YS $= 2mg(2a - x)$; YT $= 2fg(2a - x)$; YZ $= mfg$.

(*c*) Transform the star SY, SQ into the member YQ, and the star TY, TU into the member YU; whence :—

$$YQ = a - x + 2mg(2a - x) = 1/h$$
$$YU = a - x + 2fg(2a - x) = 1/k$$

(*d*) Transform the star YQ, YZ, YU into the mesh ZQ, QU, UZ; whence :—

$$ZQ = \frac{mfg(h + k) + 1}{h} = \frac{s}{h}$$
$$QU = \frac{mfg(h + k) + 1}{mfghk} = \frac{s}{mfghk}$$
$$UZ = \frac{mfg(h + k) + 1}{k} = \frac{s}{k}$$

(*e*) Combine the two parallel ZQ members and also the two parallel ZU members, thus :—

$$ZQ = \frac{ns}{nh + s} = \frac{ns}{t}$$
$$ZU = \frac{ns}{nk + s} = \frac{ns}{u}$$

(*f*) Transform the triangular mesh ZQU into the three-ray star OZ, OQ, OU; whence :—

$$OZ = \frac{n^2mfghks}{w}; \quad OQ = \frac{nsu}{w}; \quad OU = \frac{nst}{w}$$

The simplified network is then as represented in Fig. B, where the magnitude of the impedance members PQ, WV, VU is as shown and the magnitude of the members OZ, OQ, OU as given in paragraph (*f*) above.

The condition for balance of the resulting Wheatstone bridge network (for equal ratio arms) can now be written down, observing that the member OZ is in series with the battery feed and that its magnitude will not affect the equation for balance, thus :—

$$a + \frac{nsu}{w} = r + a + \frac{nst}{w}$$

$$\text{i.e.} \quad r = \frac{ns}{w}(u - t) = \frac{n^2s}{w}(k - h)$$

The advantage of the above method of treatment from the point of view of the saving of labour in the work of obtaining the condition for balance is very considerable. The reduction of the complicated network to the simple four-arm bridge is also of practical advantage, by reason of the clear picture thus presented of the balancing conditions to be met when arranging the testing apparatus.

The equation given above will require to be evaluated for x. In doing this the work is simplified by reason of the fact that in practice n, m and f are of an order

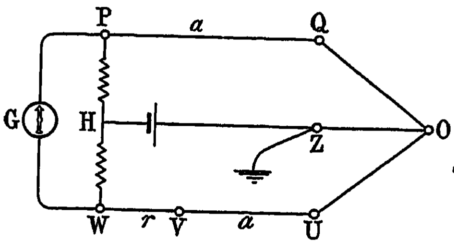

FIG. B.

10^4 to 10^5 times that of a and x. Furthermore, if a similar equation is obtained for the balancing condition (balancing resistance r') when testing from the end of the line remote from PW (this can be written down from analogy), then expressions involving n, m and f can be eliminated, and the equation for the distance (x) to the fault becomes

$$x = \frac{2ar'}{r + r'}$$

Mr. A. Rosen (*in reply*): I am grateful to Mr. Morris for drawing my attention to G. A. Campbell's article in the *Bell System Technical Journal* of July 1922, with which I was previously unacquainted. From the fact that it is not quoted in more recent articles on the subject, and also that Mr. Morris is the only one who has commented on the matter, it is evident that the theorem is new as far as engineers in this country, and no doubt in Europe generally, are concerned.

The instance given by Mr. Morris is interesting, not only as an example of the application of the star-mesh conversion, but also as a method of locating faults in underground cables which will be appreciated by cable engineers. Since the publication of the paper, I have found further instances of the more extended form of the theorem, in the development of a general theory of the interference between circuits in telephone cables.

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE: CHAIRMAN'S ADDRESS

By H. H. Harrison, Member.

"THE ART OF COMMUNICATION ENGINEERING."

(Abstract *of Address delivered at Liverpool, 3rd November,* 1924.)

In taking for my subject to-night that of Communication Engineering, I need hardly remind the members that our Institution originally existed as the Society of Telegraph Engineers and that its interests were then entirely devoted to this, the earliest, branch of our profession.

Communication engineering embraces telegraphy and telephony, either wire or radio, and also such electrical means of communication as control the movements of trains, i.e. railway signalling. Fundamentally the three sections have the same object, viz. the control from one point by one individual, or a group, of the actions of another person or collection of persons situated some distance away. The links over which the control is exercised range from a few miles to three or four thousand, and it is partly this question of distance which determines the type of link used.

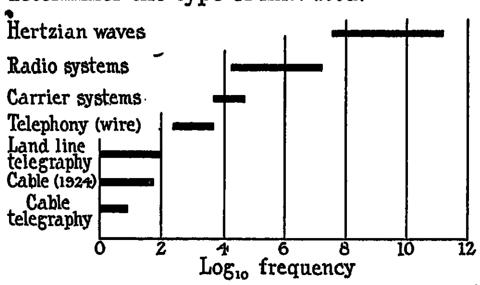

Fig. 1.—Frequency bands of different forms of communication.

To the student of these matters two tendencies have revealed themselves in the last 10 years. One is the replacement, as far as possible, of the human element by the machine. This is evidenced by the rapid growth in the adoption of printing-telegraphs, in which the telegraphic art is reduced to the mere pressing of buttons; while switching mechanisms, remotely controlled by the subscriber, are fast taking the place of the manually operated telephone exchange. This movement is in evidence over the entire world, but perhaps more so in the United States. This is partly explained by the size of that country and by the number of big cities at relatively great distances apart. In Europe, since the war, great strides have taken place in the directions indicated.

The second tendency to be noted is the gradual overlapping in technique of land-line, cable and radio telegraphy and of land-line and radio telephony due to each borrowing methods which have been developed in bringing the others to their present stage of usefulness. The interconnection of land-line and radio-telephone channels is an example of this, and both wire telegraph and telephone engineers are crossing the frontier line dividing them from the radio engineer. The common medium of exchange is the three-electrode valve and its associated circuits.

It is perhaps useful at this stage to glance at the communication frequency spectrum. Fig. 1 shows the various frequency bands used by the different systems. The plots represent the logarithms of the numbers corresponding to the width of the bands.

I propose in this address to give illustrated descriptions of the following:—

Signalling methods employed in communicating intelligence.
Various multiple methods of signalling.
The fundamentals of telephony.
The current patterns of elementary signals.
The characteristics of long and short conductors, cable and land line.
The siphon recorder.
Automatic transmission on cables.
Telephone circuits.
The advantages and disadvantages of loading.
Methods of loading in use.
Combination of loading with repeaters.
Arrangements at repeater stations.
Radio-telephony.
The band filter.
Carrier-current telegraphy and telephony.
Interlinking of wire and radio channels.

Land-line telegraphy has, except for the application of several frequencies to multiple operation, remained stationary for many years. The process of substitution of machines for manual methods of operation is steadily proceeding and manual telegraphy is dying, but dying hard.

Two recent developments in automatic telegraphy possess features which make them of some interest. Quadruplex telegraphy which provides for the simultaneous transmission of two groups of signal in one direction, and also two groups of signals in the opposite direction independently of each other, is based on a combination at each station of the single-current and double-current duplex systems. The single-current portion of the system permits of the transmission of one group of signals in each direction through changes in current intensity, and the double-current system permits of a similar additional transmission through changes of current direction irrespective of current strength. The latter is called the "A," and the former the "B" channel. The "B" signals are superposed on the "A" signals, as will be clear from Fig. 2 (*a*) in which letters F and L are set out on a current-time chart.

It will be noted from Fig. 2 that the requirements for the "A" side signals result in several reversals in direction of the current while "B" signals are in progress. These reversals produce a moment of no current

in the line. This has no influence on the "A" side relay, since this is polarized and its armature remains where last placed. The "B" side relay is, however, non-polarized and is provided with a controlling spring. With no current, its armature commences to leave the working position and return to the normal or resting position. This return movement ceases as soon as the current is re-established, but in the meantime the "B" signal has been broken, or "split" as it is termed. This is shown at the points indicated by arrows in the figure. This splitting tendency seriously limits the distance over which quadruplex operation is possible and also prevents high-speed operation of the "B" channel, although this is practicable on the "A" channel.

which also involves the connecting in phase of the several transmitters by shafting and gears has been developed. Two separate independent channels are shown in Fig. 3, but there is no limitation and three or four channels may be employed. The principle on which the method depends for obtaining more than one channel is that of division of the line time. A time unit is taken, say that of a dot impulse, and the line is given to each transmitter in turn for one-half, one-third, or one-quarter of the time unit. The transmitter star-wheels are geared together and to a revolving brush arm, which sweeps over circularly disposed contacts in pairs and gives the line to each transmitter lever TL, TL_2 in turn. The current-time chart at the right-hand side

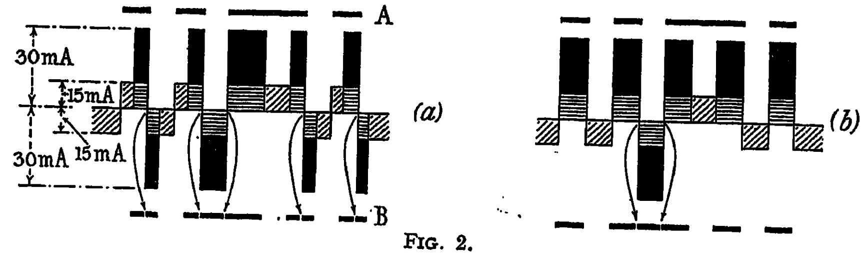

FIG. 2.

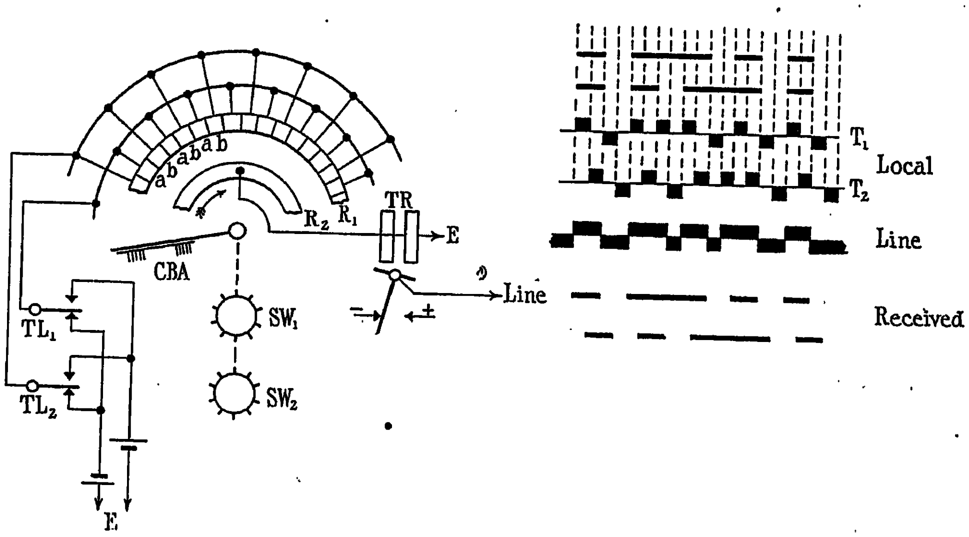

FIG. 3.

In Fig. 2 (*b*), matters are so arranged that the dot signals on both channels commence and terminate together. When this is effected—and it is secured by using automatic transmitters on both channels and gearing them together—split dot signals are impossible on the "B" channel and the dashes are only split at intervals a dot space apart. These can be bridged over by any of the known devices for this purpose, and we have a quadruple system which is capable of operating at high speeds on both channels. This ingenious step in quadruplex operation is due to Creed and Willson and constitutes a considerable advance; 130 words per minute per channel, or, together, 260 words per minute have been transmitted between London and Manchester.

Another recent contribution to land-line telegraphy

shows how the two sets of signals dovetail into each other for the letters "L" and "F." Their resultant in the line is unreadable and the system may be considered to be untappable. At the receiving end a synchronous rotary commutator is used to select the two sets of signals and distribute them to their appropriate receivers, which must be polarized.

In submarine cable telegraphy developments have taken two directions: (1) Improvements in terminal apparatus, and (2) improvements in the design and construction of the cables themselves. The first-named improvement takes the form of some amplifying device.

Most cable amplifiers consist of the siphon-recorder arrangement without the recording siphon. Three examples are given in Fig. 4.

Fig. 4 (*a*) shows the well-known Heurtley hot-wire magnifier. The receiving coil controls the movement of two fine platinum wires. Adjacent to these are two fixed wires, the system being heated by current from a local battery. When the relative positions of the wires are altered by the movements of the coil, their mutual heating effect is modified. The temperature and, therefore, the resistance of the wires in one arm of the bridge are increased and the bridge balance is upset; causing a current to flow in the local recorder.

Fig. 4 (*b*) shows an arrangement in which the magnifying means is the thermionic valve. The receiving coil has two windings, one in the cable circuit as usual

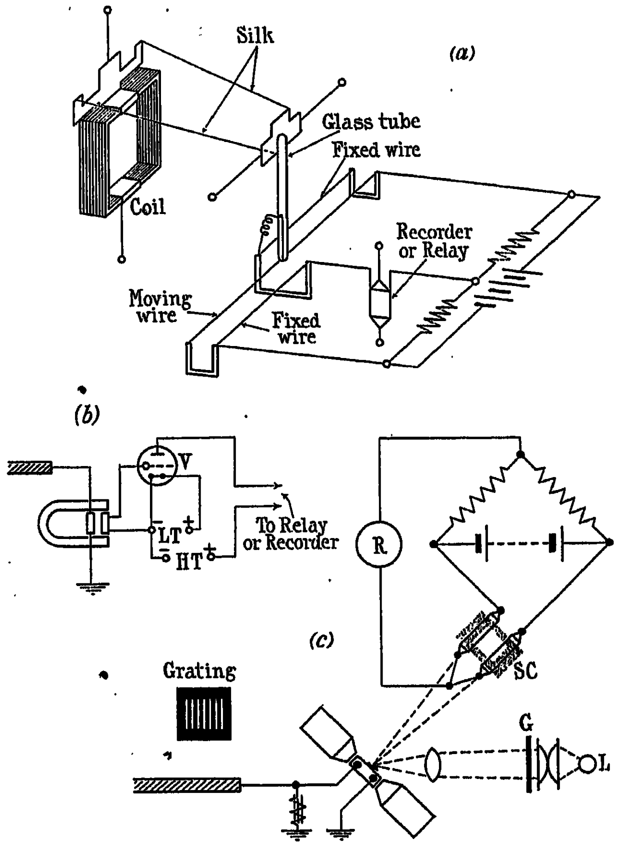

FIG. 4.

and the other so mounted that the coupling between the two coils is negligible. As the coil system oscillates in response to the cable signals, minute electromotive forces are induced in the second coil and these operate on the grid of the valve in the usual way. This amplifying arrangement is stated to give very good results; since the coil has no harness of any kind attached to it the response is very rapid and far in excess of what is actually needed. It would not, however, be applicable to block signals.

Fig. 4 (*c*) shows the arrangement of Cox's selenium-cell amplifier as used by the Pacific Cable Board. The local relay recorder (R) is in a balanced Wheatstone bridge, of which two groups of selenium cells form the third and fourth arms. By means of the optical arrangement shown, the image of a grating (G) is thrown on the two sets of cells. Minute movements of the cable receiver-coil cause abrupt variations between light and darkness and, in accordance with the well-known property of selenium, the conductivity of one bridge arm is increased while the other is decreased. An inductive shunt is placed across the cable receiver-coils. This allows the quick-acting portion of the signal elements to pass through the coils while the slowly varying part or the tail is shunted. The final signals are thus greatly improved in definition. This "shaping" is an old, well-known feature of cable telegraphy.

Amplifiers are, however, not an unmixed blessing. A long, single-wire conductor is very liable to any disturbances which prevail, and making the receiver more sensitive seriously increases this liability. Also the more sensitive the receiving apparatus, the greater is the difficulty in getting a balance which will give satisfactory duplex or two-way working. We cannot, in fact, avail ourselves of all the magnification possibilities which lie to our hands.

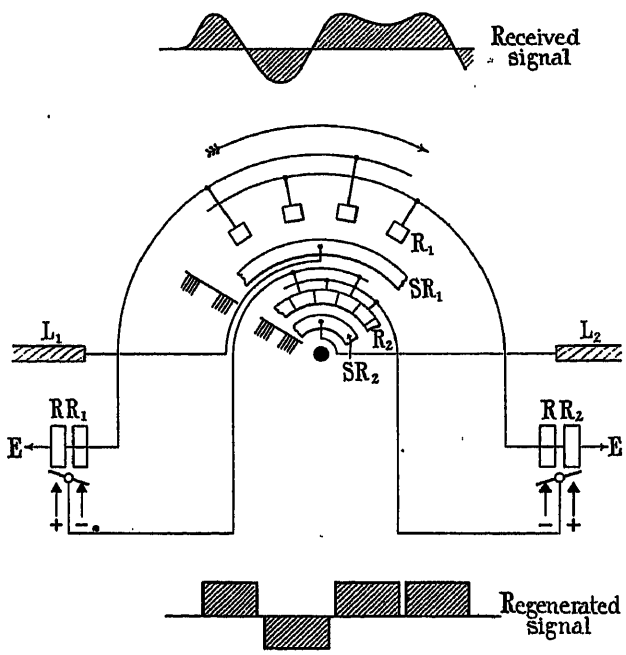

FIG. 5.

A further and more recent development in cable technique is the adoption of regenerative repeaters. The regenerative repeater is due to the eminent French telegraph engineer, the late Emile Baudot. In the ordinary form of repeater the incoming signals operate a relay which sends out current impulses from a battery or other source to the second section of the line. On long and difficult circuits this method is defective because the arriving signals at the repeater station are distorted and the relay there repeats them with further distortion, which it adds itself.

Fig. 5 shows a regenerative repeater inserted between two sections of cable and employing the cable form of morse code. At the top the letter "1" is shown as received from the cable L_1. Alternate signal elements are diverted to two receiving relays, RR_1 and RR_2 via the

solid ring (SR_1) of a rotary commutator or distributor and the short segments of ring R_1. These segments are shortened so as to pick out the middle portion of each received signal element. When a relay has been set by a signal impulse it applies current from a battery to the second line (L_2) via the segments of ring R_2 and solid ring SR_2.

It will be noted that while one relay is being set the other one is transmitting the previously received signal impulse. The setting and transmitting cycles of each relay do not overlap and good contact is assured before a signal is repeated. The rotating brush arm is driven at a constant speed, equal in segments per second to that at which the originating transmitter sends out the signal elements.

The regenerated signal, restored to its correct shape and length, is shown at the bottom of Fig. 5. This type of repeater has been carried to a high state of development by the Western Union Telegraph Co. and is in use on this company's cables. It enables the provincial offices to become extensions of the cable, and direct communication involving no retransmission is possible between Liverpool or other provincial centres and New York or Chicago.

The year 1924 has been marked by the laying of two submarine cables which have a speed of transmission, measured in letters per minute, far in excess of any previous cable. The first has been laid by the Commercial Cable Co. between this country and New York and gives a total speed of 1 200 letters per minute—600 in each direction—which is nearly twice as much as any deep-sea cable in operation at the time of laying. No particulars are available of the design, but presumably an extra heavy copper core has been provided and the electrostatic capacity kept down as much as possible.

The second cable is that between New York and the Azores, laid by the Western Union Co. This cable is loaded on the continuous plan by means of the nickel-iron alloy known as "permalloy," which has a permeability about 30 times that of the best Swedish iron. The speed obtained is 1 700 letters per minute in one direction, nearly six times that ordinarily attained. Writing in 1917, Dr. Malcolm in his book "The Theory of the Submarine Telegraph and Telephone Cable" said: "The possibilities in the future of cable telegraphy in its own sphere are as brilliant as are those of wireless telegraphy. Although the difficulties in the way of their realization must not be underestimated, none appear to be insuperable . . . there can be but little question that cable telegraphy is about to enter upon a period in which all its past achievements will be excelled." His prophecy has not been long in its fulfilment.

The submarine telephone cable has quite recently undergone a radical change in design, as evidenced by the laying of the Anglo-Dutch cable between Domburg, Walcheren and Aldeburgh (Suffolk) which was completed on the 29th August, 1924. Its length is 86 miles, and it consists of eight pairs of continuously loaded conductors, insulated with dry paper and lead-covered and armoured. The submersion was successfully accomplished and it fully met the conditions laid down in the specification. In an editorial comment the *Electrician* truly pointed out that the successful completion of this undertaking solves one of the principal engineering problems involved in the development of an international telephone service, which, when established, will play an important part in promoting better political and commercial relations between Great Britain and continental countries.

A great deal of experimental work has been conducted in Germany recently on carrier-current telegraphy. The German engineers have adopted audio frequencies of the same order with respect to amplitude as speech currents in ordinary telephony. Thus it is possible to take a pair or pairs in existing telephone cables. Repeater stations are of the same type as used for telephone purposes. In this way, six separate telegraph transmissions of 166 words per minute, say 1 000 words, over a loaded cable with an *al* of 2·3 have been obtained. The sending voltages are approximately 1 volt and no disturbance is caused to the telephone pairs in the same cable. Germany appears to be the first administration to employ audio-frequency multiple telegraphy in loaded cables, and we might prophesy that in future, at all events in countries where the distances are comparatively short, the telegraph network will be formed of twisted pairs run in telephone cables.

Radio telegraphy has progressed and is progressing. It is still not without its problems, but we cannot suppose that the large band of workers engaged in this branch of the art will be content to stand still. The "beam" system recently announced by Dr. Marconi is full of possibilities. If it realizes all the expectations of its sponsors, radio telegraphy will once again catch up with the progress recently made in wire telegraphy. Radio and wire channels interlinked will permit of international telegraphy and telephony on a scale not contemplated hitherto. At no period in the development of the communication art has progress been so rapid as it is to-day. This results from the intensive research work carried on continuously by the workers in the different fields.

No paper dealing with this subject should omit a reference to the extraordinary development taking place in the replacement of manually operated telephone exchanges by machine-switching methods. It is no secret that London is being converted from manual to machine operation. The work of installation has already commenced and will occupy from 15 to 20 years before it is complete. The transition period has given rise to serious problems, which have been satisfactorily solved by the Post Office and other engineers who are members of this Institution. Tokio is about to undergo conversion, while Buenos Aires has been in course of conversion for some years.

To the younger members I should like to address a few remarks: I hope that I have been able to show that communication engineering is interesting. It is more than this. It involves just as much engineering consideration as the heavy and, perhaps, more spectacular branch of our profession. While it has been the subject of good-humoured contempt in the past, it is rapidly acquiring a standing and dignity to which it is fully entitled. For many years to come it will offer to the young trained engineer an opening for his talents, and it is not without its prizes too.

WIRELESS TELEGRAPH VALVE TRANSMITTERS EMPLOYING RECTIFIED ALTERNATING CURRENT.

By G SHEARING, B.Sc., Member.

(*Paper received 7th August, and read before the* WIRELESS SECTION *3rd December*, 1924.)

SUMMARY.

The paper describes the development of some of the valve transmitters employing rectified power for naval purposes, from December 1918, onwards. The earlier work is briefly reviewed and general considerations of design for ship conditions are dealt with.

A description is given of the method of calculation of the geometry of the rectifying valve electrodes and of the power loss.

Some of the types of transmitter circuits employed are described, also detail circuit improvements for satisfactory working.

Arrangements of valves in series and the use of coupled circuits for drying-out wet aerial systems, also separate grid-excitation circuit arrangements, are dealt with.

Experimental circuits for the reduction of harmonic interference, also the arrangements adopted for signalling by grid potential control, are discussed.

Finally, the design of the transmitting valve electrodes is dealt with and the question of valve rating is discussed.

TABLE OF CONTENTS.

INTRODUCTION.

This paper deals with some of the valve wireless telegraph transmitters and power supply circuits utilizing rectified current, which have been developed in the Experimental Department of H.M. Signal School for naval purposes from December 1918, onwards. The earlier experimental work, which is briefly reviewed, had indicated that the valve transmitter would supersede both arc and spark transmitters for naval purposes, and this conclusion has since been confirmed by the results obtained, in experimental and routine working, from valve transmitters installed during and since 1919 in the Fleet and in Admiralty shore stations.

SECTION 1.

Earlier work.—The experimental war work * on transmitting valves and circuits carried out from 1915 to 1918 led up to the successful production early in 1918 of a valve transmitter for continuous-wave transmissions which could compete fairly satisfactorily with an arc transmitter of 5 kW supply power from d.c. mains on the same range of wave-lengths as regards received signal strength and distance, and was much superior as regards speed of working. This transmitter employed one glass transmitting valve, type T4 and, later, T4A, of 400 watts anode rating. An alternative design of increased power, which was used in a few cases, employed two T4A valves in parallel. Also, prior to these, valve transmitters of smaller powers had been successfully employed in ships.

The source of h.t. power supply for the T4A valve was the spark-telegraphy alternator and single-phase transformer, the high-voltage direct current required for the anode of the transmitting valve being obtained from a two-wave rectifier unit with smoothing condenser. No special switching arrangements were supplied for interrupted continuous wave (I.C.W.) transmissions, but the change from continuous waves (C.W.) to I.C.W. could be made when required, either by cutting the rectifier unit out of circuit or by disconnecting the smoothing condenser.

For small ships and for the second offices of heavy ships the usual installations were either (1) a spark transmitter supplied from a rotary converter and h.t. transformer and an arc transmitter of 5 kW d.c. input, or (2) the spark set together with the valve C.W. transmitter having one T4A valve. In this case the valve set received its power via the spark h.t. transformer.

* C. L. FORTESCUE: *Report of the British Association for the Advancement of Science*, 1919, and *Radio Review*, 1919, vol. 1, p. 83; B. S. GOSSLING: *Journal I.E.E.*, 1920, vol. 58, p. 670; G. STEAD: *Ibid.*, 1920, vol. 58, p. 107.

Two C.W. valve transmitters of increased power, employing three T4A valves in parallel, were designed and built at the Signal School towards the end of 1918, and were installed at Aberdeen and Ipswich in January and March 1919, respectively. These sets have since been in continuous use for routine work; at Aberdeen an aerial current of 50 amperes was obtained on a wave-length of 3 100 m during the tuning trials in January 1919, the aerial capacity being 2·8 jars.

The results obtained with these sets at shore stations and at sea were so satisfactory that a demand arose during 1919 for valve transmitters of increased power and robustness of design which would not only cover the required range of C.W. wave-lengths but also be suitable for I.C.W. transmissions on the spark range of wave-lengths. In this way the dual arrangement of spark and C.W. valve, or alternatively spark and arc, was replaced by a single-valve transmitter capable of working at a greatly increased speed, the keying of the circuits being arranged for the operator to listen-through during the intervals of his transmission signals.

General considerations.—Arising out of the results obtained with the above sets, the further development of medium-power and high-power valve transmitters for routine work which was put in hand during 1919–20 may be summarized as follows:—

(*a*) Transmitters for Fleet use capable of supplying power of from 2 kW to 10 kW to the aerial under normal conditions and occupying the minimum possible space for satisfactory routine operation in existing wireless telegraph offices; and

(*b*) Transmitters for shore stations for aerial powers up to 30 kW of much more open design.

In addition, certain transmitters of much higher power than (*b*) have been developed.

In the majority of cases the transmitter has been designed to utilize already existing sources of power supply. In this respect it has been fortunate that the power plant for the old spark-telegraphy transmitters was usually suitable for a valve transmitter. The change-over from spark to valve has for this reason been very economical, bearing in mind the advantages obtained from the installation of the valve transmitter.

The main conditions to be aimed at in the design of the valve sets may be enumerated as follows:—

(1) Reliability of working under seagoing conditions, including gunfire.
(2) Satisfactory operation with the insulation of the aerial oscillatory circuit subjected to severely wet conditions.
(3) Robust design of component parts.
(4) Change of wave-length in short time.
(5) Simplicity of control apparatus.
(6) Reasonably efficient working over a very wide range of wave-lengths.
(7) Protection of h.t. power plant and component parts of transmitter from breakdown.
(8) Ready access to each component part.

The total space available has usually been very limited in naval ships and it has been difficult to design a set capable of accommodation so that the required aerial power could be obtained over a wide range of wave-lengths without sparking to earth from the oscillatory circuits. The solution was largely assisted by the successful introduction of the silica valve during 1920; this required less space for the required anode dissipation compared with glass transmitting valves.

The valve transmitters evolved up to 1918 had their apparatus mounted on wood panels to which the valves and other components were fixed. This method was not considered sufficiently robust, and panels of transmitters were developed whose sides were usually composed of angle metal with the component parts bolted to straps of metal or insulation as required, the panel fronts being enclosed with expanded metal capable of removal when necessary. Usually these panels required subdivision to enable them to be readily passed down the hatchways of ships. This system, introduced by Mr. H. Morris-Airey at the end of 1918, has facilitated the standardization, transport and installation of transmitters in ships in the various dockyards.

SECTION 2.

The production of h.t. power.—The majority of the C.W.–I.C.W. transmitters use rectified single-phase

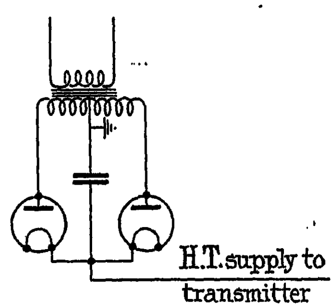

FIG. 1.

alternating current employing two-wave rectification as in the simple circuit shown in Fig. 1. For high powers multiphase rectification is employed.

The single-phase circuit has been described by Prof. C. L. Fortescue, who has deduced formulæ * for design calculations based on the assumption that the saturation current flows through the rectifying valve for the time of each period of the a.c. supply when the anode is positive to the filament.

This assumption was valid for the earlier valve transmitters employing h.t. power supply considerably less than the full power output of the alternator and transformer and having rectifying-valve filaments of small electronic emission. With increase of the aerial power requirements it has been found essential to obtain as high an efficiency of rectification as possible, as the motor-alternators installed were of limited output. The rectifying valves have been designed with liberal filament emission so that, with normal circuit adjustments corresponding to full power, filament saturation

* *Proceedings of the Physical Society*, 1919, vol. 31, p. 319.

does not occur. The increase of filament power required, usually obtained from an auxiliary motor-alternator, has been small in comparison with the gain resulting from the increase of rectified power available for the transmitter.

The exact calculation of the efficiency of a rectifier unit is complex, as has been pointed out by other writers, due to the effects of the transformer impedance and the shape of the anode current/voltage characteristics of the valves. Other factors are the ripple on the rectified potential and the impedance of the transmitting network. The following approximations for a two-wave single-phase supply have enabled design calculations for the valves to be made sufficiently accurately.

As regards the valve itself, the well-known formula for the space current, assuming a filament of infinite emission, is

$$i = 2 \cdot 93 \times 10^{-5} \frac{v^{3/2}}{d_a} l \quad . \quad . \quad . \quad . \quad (1)$$

where d_a = diameter of anode or plate;
l = effective length of anode; and
v = anode-filament P.D.

For the case of hard valves, however, it is found in practice, for the maximum P.D.'s in use for valve as conductor* and with filaments of limited but considerably greater emission than the maximum required, that the relation between the P.D. and anode current may be expressed approximately by :—

$$i_r = \frac{V \sin \omega t - (k + v)}{r} \text{ when } V \sin \omega t > (k + v) \,. \quad (2)$$

where i_r = anode current;
$V \sin \omega t$ = anode potential, assumed sinusoidal;
k = constant;
v = filament potential; and
r = apparent resistance of valve.

The ripple of the smoothing-condenser voltage is strictly dependent on exponential and sinusoidal functions. As, however, the ripple is of small magnitude relative to the mean potential, the assumption has been made, for calculating the rectifier power loss, that the ripple can be represented by straight lines covering each period of the a.c. supply. Referring to Figs. 1 and 2, let :—

$V \sin \omega t$ = instantaneous transformer line voltage to mid-point;
r = apparent resistance of each rectifying valve;
i_r = instantaneous valve current;
V_0 = mean rectified voltage;
C = smoothing condenser capacity;
I_0 = mean current output of condenser;
R = equivalent load resistance, assumed non-inductive;
v_c = permissible maximum ripple about mean value V_0; and
$v_1 = V_0 - v_c$; $v_2 = V_0 + v_c$.

For the instant of minimum condenser voltage, the current through one rectifying valve is equal to that in the transmitting network.

* That is, when the anode potential is positive to that of the filament.

$$\text{Hence } \frac{V \sin \theta - (k + v_1)}{r} = \frac{v_1}{R};$$

$$\sin \theta = \frac{1}{V}\left\{\frac{v_1(R + r)}{R} + k\right\} \quad . \quad (3)$$

$$\text{Similarly} \quad \sin \alpha = \frac{1}{V}\left\{\frac{v_2(R + r)}{R} + k\right\} \quad . \quad . \quad . \quad (4)$$

The current i_r for the angle ωt between the angles θ and α

$$= \frac{V \sin \omega t - [k + v_1 + 2v_c(\omega t - \theta)/(\alpha - \theta)]}{r} \quad (5)$$

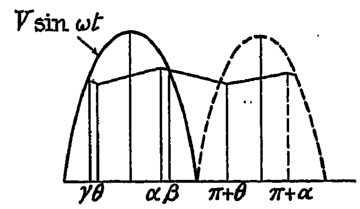

FIG. 2.

The energy used in the rectifying valves for the time between the angles θ and α is

$$\frac{1}{r\omega}\int_\theta^\alpha \left[\left\{V \sin \omega t - \left(k + v_1 + 2v_c\frac{\omega t - \theta}{\alpha - \theta}\right)\right\}\right.$$
$$\left.\left\{V \sin \omega t - \left(v_1 + 2v_c\frac{\omega t - \theta}{\alpha - \theta}\right)\right\}\right] d\omega t$$
$$= \frac{1}{r\omega}\left[\frac{V^2}{2}(\alpha - \theta - \sin \alpha \cos \alpha + \sin \theta \cos \theta)\right.$$
$$+ V(k + 2v_1)(\cos\alpha - \cos\theta) - 4Vv_c\left(\frac{\sin\alpha - \sin\theta}{\alpha - \theta} - \cos\alpha\right)$$
$$\left. + \{kv_1 + kv_c + v_1^2 + 2v_1v_c + \tfrac{4}{3}v_c^2\}(\alpha - \theta)\right] \quad . \quad . \quad (6)$$

and the rectified energy is

$$\frac{1}{r\omega}\int_\theta^\alpha \left[\left(v_1 + 2v_c\frac{\omega t - \theta}{\alpha - \theta}\right)\right.$$
$$\left.\left\{V \sin \omega t - \left(k + v_1 + 2v_c\frac{\omega t - \theta}{\alpha - \theta}\right)\right\}\right] d\omega t$$
$$= \frac{1}{r\omega}\left\{Vv_1(\cos\theta - \cos\alpha) + 2Vv_c\left(\frac{\sin\alpha - \sin\theta}{\alpha - \theta} - \cos\alpha\right)\right.$$
$$\left. - (kv_1 + kv_c + v_1^2 + 2v_1v_c + \tfrac{4}{3}v_c^2)(\alpha - \theta)\right\} \quad . \quad . \quad (7)$$

To determine the angles β and γ for zero current we have as an approximation

$$V \sin \beta = k + v_2 - 2v_c\frac{\beta - \alpha}{\pi + \theta - \alpha} \quad . \quad . \quad (8)$$

$$V \sin \gamma = k + v_1 + 2v_c\frac{\theta - \gamma}{\pi + \theta - \alpha} \quad . \quad . \quad (9)$$

The energy expended in the rectifying valves for the times between the angles θ and γ and the angles β and a is approximately

$$\frac{1}{4r\omega}(V\sin\theta - k - v_1)^2(\theta-\gamma) + \frac{1}{4r\omega}(V\sin a - k - v_2)^2(\beta - a) \quad . \quad (10)$$

and the energy supplied from the transformer for these times is approximately

$$\frac{1}{2r\omega}\int_{\gamma}^{\theta}(V\sin\theta - k - v_1)(V\sin\omega t)d\omega t$$

$$= \frac{1}{2r\omega}(\cos\theta - \cos\gamma)(Vv_1 + kV - V^2\sin\theta) \quad (10a)$$

and $\dfrac{1}{2r\omega}(\cos\beta - \cos a)(Vv_2 + kV - V^2\sin a) \quad (10b)$

Summarizing the above we have :—

Mean power loss per period in the valves.

$$\begin{aligned} W_r = \frac{1}{\pi r}\Big[& \frac{V^2}{2}(a - \theta - \sin a\cos a + \sin\theta\cos\theta) \\ & + V(k + 2v_1)(\cos a - \cos\theta) \\ & - 4Vv_c\Big(\frac{\sin a - \sin\theta}{a-\theta} - \cos a\Big) \\ & + (kv_1 + kv_c + v_1^2 + 2v_1v_c + \tfrac{4}{3}v_c^2)(a-\theta) \\ & + \tfrac{1}{4}\{(V\sin\theta - k - v_1)^2(\theta - \gamma) \\ & + (V\sin a - k - v_2)^2(\beta - a)\}\Big] \quad . \quad . \quad (11) \end{aligned}$$

Mean power rectified.

$$\begin{aligned} W_{TR} = \frac{1}{\pi r}\Big[& Vv_1(\cos\theta - \cos a) \\ & + 2Vv_c\Big(\frac{\sin a - \sin\theta}{a-\theta} - \cos a\Big) \\ & - (kv_1 + kv_c + v_1^2 + 2v_1v_c + \tfrac{4}{3}v_c^2)(a-\theta) \\ & + \tfrac{1}{2}\{(\cos\theta - \cos\gamma)(Vv_1 + kV - V^2\sin\theta) \\ & + (\cos\beta - \cos a)(Vv_2 + kV - V^2\sin a)\} \\ & - \tfrac{1}{4}\{(V\sin\theta - k - v_1)^2(\theta-\gamma) \\ & + (V\sin a - k - v_2)^2(\beta - a)\}\Big] \quad . \quad (12) \end{aligned}$$

If we neglect the terms involving the angles γ and β, which are small, then

$$\begin{aligned} W_{TR} = \frac{1}{\pi r}\Big[& Vv_1(\cos\theta - \cos a) \\ & + 2Vv_c\Big(\frac{\sin a - \sin\theta}{a-\theta} - \cos a\Big) \\ & - (kv_1 + kv_c + v_1^2 + 2v_1v_c + \tfrac{4}{3}v_c^2)(a-\theta)\Big] \quad (13) \end{aligned}$$

and

$$\begin{aligned} W_r = \frac{1}{\pi r}\Big[& \frac{V^2}{2}(a - \theta - \sin a\cos a + \sin\theta\cos\theta) \\ & + V(k+2v_1)(\cos a - \cos\theta) - 4Vv_c\Big(\frac{\sin a - \sin\theta}{a-\theta} - \cos a\Big) \\ & + \{kv_1 + kv_c + v_1^2 + 2v_1v_c + \tfrac{4}{3}v_c^2\}(a-\theta)\Big] \quad . \quad . \quad (14) \end{aligned}$$

Also, if we equate the quantity delivered to the load circuit to that supplied through the rectifying valve, we have, assuming no leakage current through the smoothing condenser,

$$I_0 \times \frac{\pi}{\omega} = \frac{1}{r\omega}\int_{\theta}^{a}\Big\{V\sin\omega t - \Big(k + v_1 + 2v_c\frac{\omega t - \theta}{a-\theta}\Big)\Big\}d\omega t$$

$$r = \frac{V(\cos\theta - \cos a) - (k + v_1 + v_c)(a-\theta)}{I_0\pi} \quad . \quad . \quad (15)$$

and the value of the smoothing condenser, if no filter circuit is employed, is approximately

$$C = \frac{I_0}{\omega}\{\pi - (a - \theta)\}\frac{1}{2v_c} \quad . \quad . \quad . \quad (16)$$

For the case of negligibly small ripple, Equations (3), (4), (14) and (13) reduce to

$$\sin\theta = \sin a = \frac{1}{V}\Big\{V_0\frac{(R+r)}{R} + k\Big\} . \quad . \quad (17)$$

$$\begin{aligned} W_r = \frac{1}{\pi r}\Big\{ & \frac{V^2}{2}(\pi - 2\theta + 2\sin\theta\cos\theta) \\ & + V(k + 2V_0)(-2\cos\theta) + (kV_0 + V_0^2)(\pi - 2\theta)\Big\} \quad . \quad (18) \end{aligned}$$

$$W_{TR} = \frac{1}{\pi r}\{VV_0(2\cos\theta) - (kV_0 + V_0^2)(\pi - 2\theta)\} \quad (19)$$

The design of the rectifying-valve electrodes and the smoothing condenser has usually been based on the following available data :—

(a) The mean supply voltage and power to the transmitter.
(b) The order of permissible voltage ripple.
(c) The maximum anode-filament valve P.D. with anode positive.

The value adopted for (c) determines the efficiency of rectification. For transmitter supply voltages of 10 000 to 12 000 utilizing silica rectifying valves with molybdenum anodes, the valves have been so designed that the maximum current is well below that for filament saturation for a maximum P.D. of 3 000 volts with anode positive. The value of k is of the order of 300 volts for valves with molybdenum anodes designed for an operating power loss up to 5 kW per valve.

As an example let us take the case of a valve transmitter requiring 15 kW of rectified power at a mean anode voltage of 10 000, the smoothing condenser ripple to be of the order of $\pm$ 4 per cent and the maximum conducting P.D. for the valve 3 000 volts.

Equations (15) and (16) enable the resistance r of the rectifying valve and the smoothing condenser capacity C to be calculated with a sufficiently close accuracy, if we assume $\sin\theta = (v_1 + k)/V$ and $\sin a = (v_2 + k)/V$ as approximations. This gives $r = 494$ ohms, $C = 1\cdot 56\,\mu$F.

Adopting this value for r, the power loss may be calculated from Equation (11), having first re-calculated the angles θ and a from Equations (3) and (4), and the angles β and γ from Equations (8) and (9). This gives

$\theta = 54° 42'$, $\alpha = 118° 4'$, $\beta = 125°$, $\gamma = 49° 30'$ and the power loss in the rectifying valves $= 3\cdot6$ kW (or $1\cdot8$ kW per valve).

The efficiency of rectification $= 15/18\cdot6 = 81$ per cent.

The valve filament has to be such that it will give a space current of $(3\,000 - 300)/494 = 5\cdot46$ amperes with the filament well below saturation.

The curves of Fig. 3 show the results of calculations for various anode voltages, assuming a constant maximum permissible conducting P.D. for the valve. They illustrate the increased efficiency to be obtained from rectifying at as high a rectified voltage as practicable, but in this connection due regard has to be paid to the maximum permissible voltage which the valve will withstand as an insulator, i.e. when the anode is negative to the filament. It has been usual to specify an acceptance-test P.D. of 40 000 volts with the valve as insulator and the anode not heated, but experience has shown that for average valves it is inadvisable to go beyond 14 000 volts (corresponding to 31 000 volts maximum P.D.) if the valves are to be worked at full power dissipation for long periods.

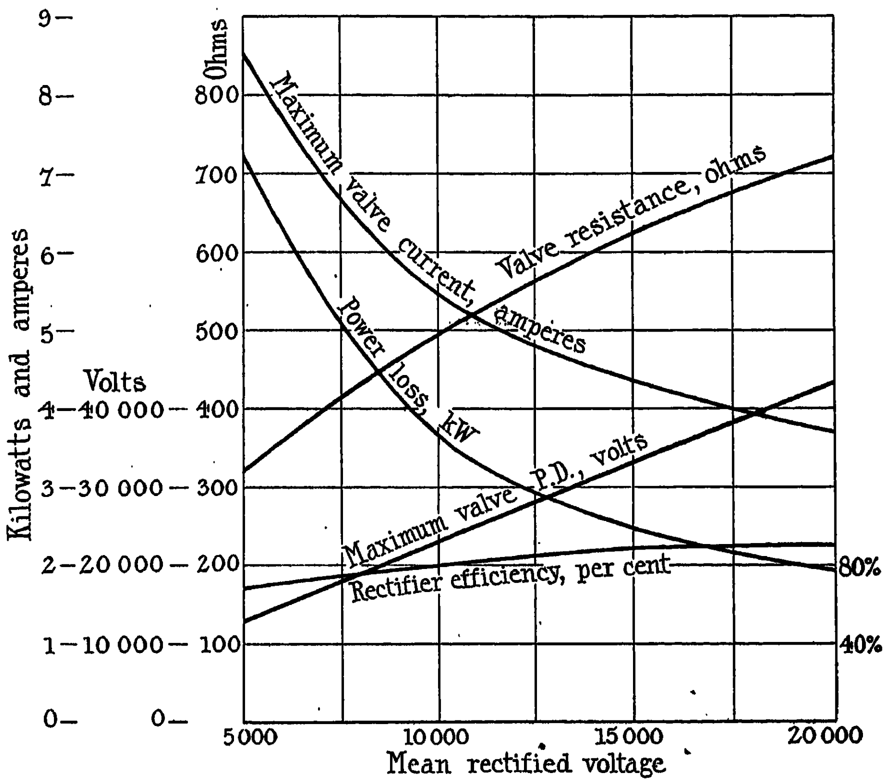

FIG. 3.—Calculated curves for constant rectified power of 15 kW.

Furthermore, as the valve transmitters have to be designed for a very large range of wave-lengths it is difficult at some wave-lengths to avoid the operation of the transmitter at aerial circuit adjustments corresponding to full power supply at lower voltages. For this reason the anodes of the valves are designed for full power supply at a rectified potential of 10 000 volts. Similar calculations may be made for other values of maximum positive anode-filament P.D.; reducing this P.D. corresponds to increased rectifying efficiency.

The filaments are usually designed for 50 per cent greater filament emission than the calculated value. Usually the length of the filament is settled upon as a first approximation, and the filament diameter can then be calculated. The filament length fixes the anode length. To estimate the anode diameter it usually suffices to calculate the diameter of the valve anode whose mean resistance from the space current equation (1) is equal to the required value.

From this equation $\dfrac{dv}{di} = \dfrac{d_a v^{-\frac{1}{2}}}{k}$

where $k' = 2\cdot93 \times 10^{-5} \times l \times 1\cdot5$

and mean value

$$= r = \frac{d_a}{V'}\int_0^{V'} \frac{v^{-\frac{1}{2}}dv}{k'} = \frac{2d_a}{k'\sqrt{V'}}$$

where V' = maximum anode-filament P.D., hence the valve anode diameter should not be greater than

$$k'\sqrt{V'} \times \tfrac{1}{2}r$$

The filament diameter for the filament emission required was calculated to be $0\cdot065$ cm for an effective

length (loop) of 28 cm.* For an anode of length 14 cm, $k' = 615 \times 10^{-6}$, $V'^{\frac{1}{2}} = \sqrt{3\,000} = 54 \cdot 8$, $d_a = 494/2 \times 615 \times 10^{-6} \times 54 \cdot 8 = 8 \cdot 3$ cm as maximum value. A molybdenum anode of these dimensions is sufficiently large for the required anode dissipation. A series of calculations for various lengths of filament enables the most economical anode to be determined.

The change of power each quarter-period

$$= 23 \cdot 1\sqrt{2} \times 27 \cdot 6\sqrt{2} = 1\,275 \text{ watts.}$$

The change of energy $= 1\,275/(4f)$ joules $= 76 \cdot 5/f$ calories for frequency f. The total length of the tungsten filament, allowing for end corrections, is

TABLE 1.

Type	Anode (Molybdenum)		Static bombard-ment	Filament			Rectified power; 2-wave rectification			Maximum conducting P.D.	Test voltage between electrodes
	Length	Diam.		V	I	Power	V_0	I_0	Power		
	cm	cm	kW	volts	amps.	kW	volts	amps.	kW	volts	volts
NU21 (silica) ..	9·5	8·0	3·0	18·5	16·9	0·31	11 000	1·0	11	3 000	40 000
NU22 (silica) ..	14·5	8·0	4·5	25·9	21·7	0·56	12 000	1·5	18	3 000	40 000
NU23 (silica) ..	30·0	12·0	20 to 25	33·0	51·0	1·68	14 000	3·6	50	4 000	50 000

The loop form of filament with cylindrical anode has been invariably used and, to secure uniformity of electron current in the two sides of the loop at any instant for alternating-current supply, a small double-wound inductance with mid-point tapping, known as an equalizing coil, has been placed across each filament. The electron current is taken from this mid-point, the two halves of the inductance being wound bifilarly so that each has the same inductance. The coils can be placed immediatley adjacent to each valve filament, and separate filament regulation is permissible.

An approximate computation of the effect of the filament supply frequency may be made by assuming that the filament temperature follows the energy change per quarter period. Let us take as an example the above filament requiring 27·6 amperes at 23·1 volts at a temperature of 2 480° K.

35·8 cm, its mass = 2·26 g, and its specific heat = 0·034. The mean temperature-change

$$= \frac{76 \cdot 5}{0 \cdot 034 \times 2 \cdot 26 \times f} = \frac{995 \text{ deg. C.}}{f} = 4 \text{ deg. C. for } f = 250$$

Hence for $f = 250$ there is a temperature variation not greater than $\pm$ 2·0 deg. C. every half-period.

The effect of unequal currents through individual valves of a rectifying system is reduced as much as practicable by rheostat control, and for quick visual indication it has been found convenient to place in each line small metal-filament lamps with resistance shunts so that each lamp glows brightly at full power.

Data relating to the electrodes for standard designs of rectifying valves are given in Table 1.

Two-wave rectifier unit.—Fig. 4 shows a typical unit for supply power up to 30 kW with smoothing condenser and switching arrangements whereby the anodes of the transmitter may be readily supplied with either

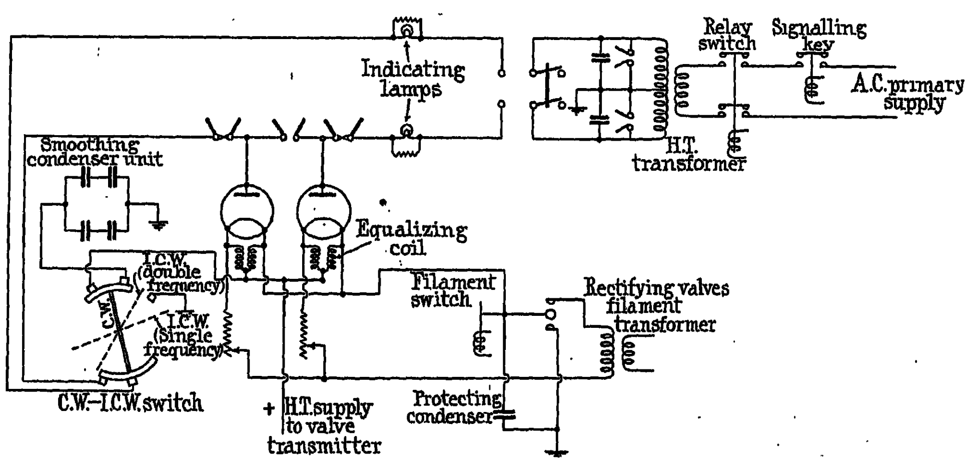

FIG. 4.

* For filament calculations see G. STEAD: *Journal I.E.E.*, 1920, vol. 58, p. 107.

a steady potential for C.W. transmissions or varying potential for I.C.W. transmissions.

Separate rheostat control is provided for each valve filament, which, in addition, is fitted with an equalizing coil. The filament supply switch is connected so that

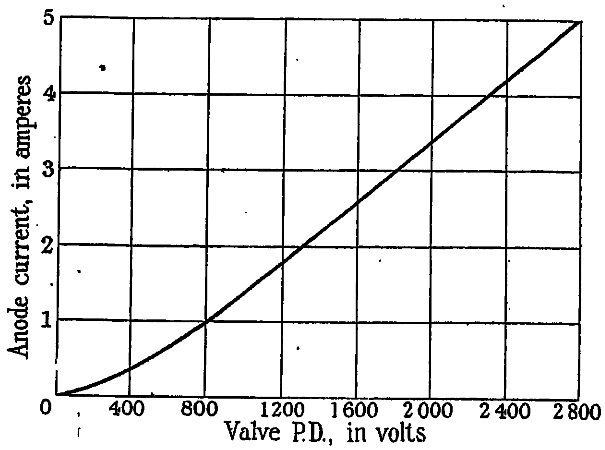

FIG. 5.—Anode current and valve P.D. Rectifying valve type NU 22.

the smoothing condenser is short-circuited to earth when the valve filaments are switched off. The smoothing condenser may consist either of condensers arranged in series-parallel as shown, or, for cases where the ripple of the supply voltage to the transmitter must be

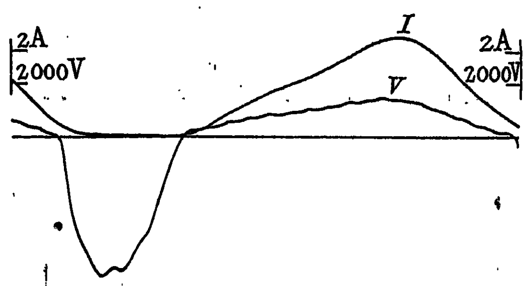

FIG. 6.—Valve current and valve P.D. for rectifying valve type NU 22. $f = 50$.

negligibly small, a filter circuit of chokes and condensers may be employed.

Horn-break fuses are provided in each line to protect the valves and transformer from short-circuiting of

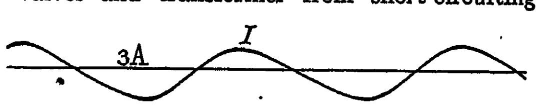

FIG. 7.—Two-wave rectification. Resultant rectified current; $f = 50$.

the smoothing condenser; these are combined with spark-gaps across the transformer. It has been found necessary also to insert across each line of the transformer secondary two small condensers of the order of one to five jars' capacity with the mid-point earthed as shown, to avoid high potential-rises which may otherwise occur and cause breakdown due to high-frequency induction in the h.t. supply lines. It is naturally very important that the high-frequency circuits should be as far away as possible from these lines, but the danger of stray induction due to the cramped conditions under which the sets are fitted cannot be entirely avoided.

A three-way switch has usually been fitted to enable a ready change to be made from C.W. to I.C.W. at

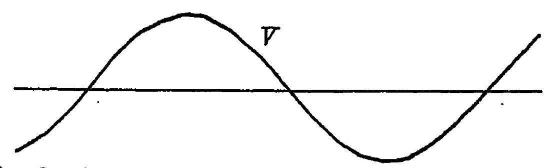

FIG. 8.—Open-circuit voltage (R.M.S.) = 5 750; $f = 50$.

either the frequency or twice the frequency of the alternator. For I.C.W. at twice the alternator frequency the smoothing condenser is disconnected from the valve filaments and earthed. For I.C.W. at the alternator frequency one line of the h.t. supply is also broken. Retaining the rectifying valves for the I.C.W. transmissions enables the change from C.W. to I.C.W. to be made with simple circuit adjustments, but in certain

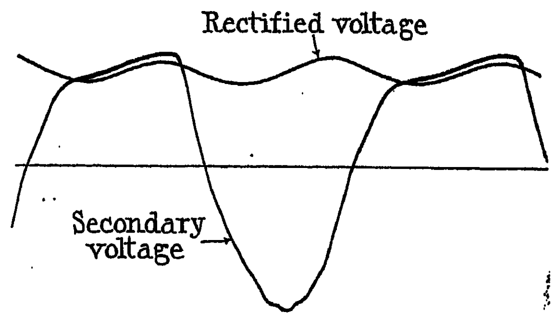

FIG. 9.—Two-wave rectification. Rectified voltage = 5 400; smoothing condenser 1 μF; rectified current = 0·23 ampere; $f = 50$.

cases I.C.W. is obtained by direct connection of the transmitter to one of the h.t. lines, which has the disadvantage that the transmitting valve is directly subjected to the alternating potential.

Experimental results.—The oscillograms of Figs. 6 to 11 inclusive have been obtained for valves of type NU 22 which approximates to the design outlined on pages 318 to 320. Those taken for a 50-period supply enable a voltage/current characteristic of the valve to be deduced, and from these and similar curves at in-

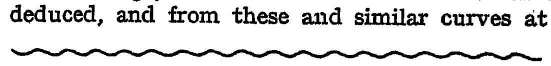

FIG. 10.—Curve of voltage ripple; smoothing condenser 1 μF; $V_0 = 9\,000$ volts; $I_0 = 1{\cdot}0$ ampere; $f = 300$.

creased voltages it is found that the valve is well below saturation for currents of the order of 5 to 6 amperes. The mean characteristic obtained from oscillograms is given in Fig. 5.

In connection with the voltage wave-form obtained

wire with multi-layer turns, and in most cases aerial circuit tuning by means of a large, coarse tapping coil and a smaller, fine tapping coil has been employed, very fine adjustments being obtained by a continuously adjustable small copper tube or strip coil. For the longer wave-lengths the anode tapping for best operation of the valve is usually intermediate between tappings on the coarse coil, and to enable best tappings to be obtained the coil section has been shunted by a coil of inductance considerably greater than that of the section. The anode tapping connection is then made to a continuously adjustable contact on this coil, which may for convenience be located in the valve panels, the best adjustment during operation being obtained by a switch operated from the panel front.

E.M.F. ωMI_1, and the anode voltage V_a is approximately at 90° to I_1, neglecting the mutual grid induced E.M.F. in the oscillatory circuit coupling coil and the P.D. across the anode condenser.

A difficulty experienced with the early sets when continuously changing wave-lengths, was the danger of operators transmitting with the grid variable condenser adjusted to such a position of increased capacity over the correct value that excessive grid currents were set up. These excessive currents caused breakdown either of the coil or condenser insulation or overheating of the grid-leak resistance, since increase of grid oscillatory current gives a corresponding increase of grid-leak current.

This danger has been minimized by the simple expedi-

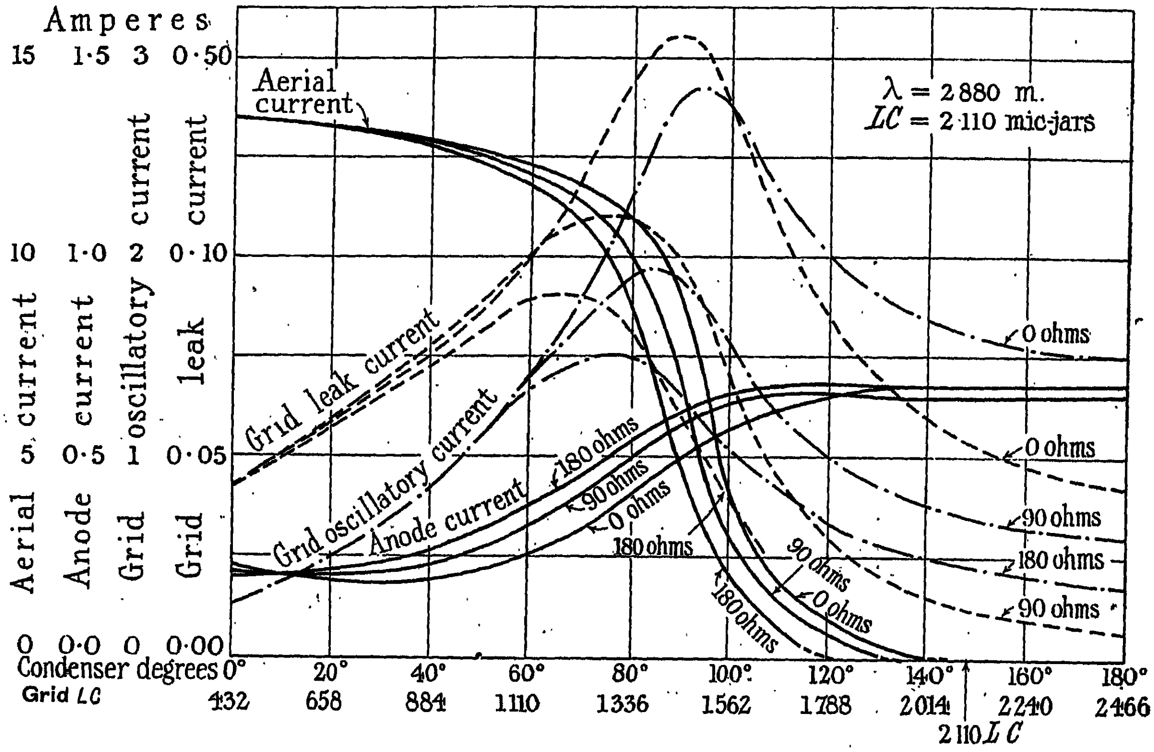

FIG. 19

Grid coupling coil circuits: inductive coupling.—The coils have been mainly of disc construction or partially disc and cylinder, the grid coil being usually shunted by a variable condenser. For ship sets giving aerial powers of the order of 2 kW the adjustments which have usually been provided are those for varying (i) turns of grid circuit coil, (ii) mutual coupling to aerial circuit coil, (iii) capacity of variable condenser, or (iv) turns of aerial circuit coil.

The vector diagram of Fig. 18 for the case of the circuit of Fig. 17 illustrates the conditions for proper direction of the grid coupling coil, neglecting the effect of the grid leak and valve circuit and of the anode condenser circuit. The grid current i_g leads over the grid induced E.M.F. by an angle which approximates to 90°. The oscillatory current I_1 is at 90° to the induced

ent of placing a resistance in the grid oscillatory circuit. Provided its value is not too high, the aerial, anode-supply and grid-circuit currents are practically unaltered with the condenser in the correct position; on the other hand, the maximum value of the grid current i_g is considerably reduced. When carbon lamps are used, or a lamp shunted by a resistance, a visual indication of incorrect dangerous adjustment is afforded. The experimentally determined curves of Fig. 19 illustrate the effect; the curves corresponding to the use of resistance coincide with the corresponding curves for no resistance, when the grid condenser adjustment corresponds to minimum anode current. For incorrect adjustments corresponding to increased capacity, when the value of LC for the grid oscillatory circuit approaches that for the oscillatory circuit, the resis-

tance reduces the maximum values considerably with automatic protection of the grid circuit.

In the vector diagram shown in Fig. 18 the effect of the grid leak and of the valve resistance from grid to filament has been neglected. This apparent valve

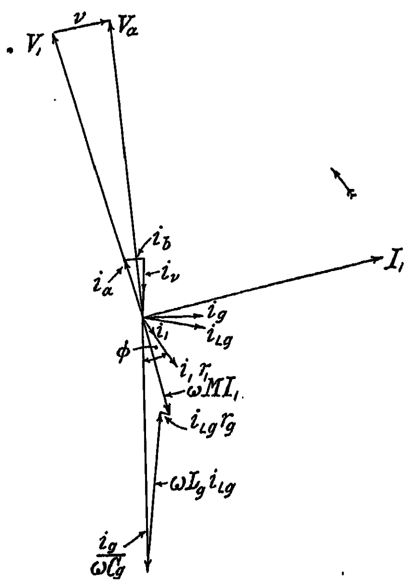

FIG. 20.

resistance will vary in value with the variation of grid potential; it will be a minimum when the grid-filament voltage is a maximum and positive. It is of interest to note in general the effect of a grid-filament resistance of value r_1. Referring to Fig. 17, the impedance of the grid leak and valve grid-filament circuit in parallel with the condenser C_g is :—

$$\frac{r_1(1 + r_L^2\omega^2c_L^2) + r_L}{1 + r_L^2\omega^2c_L^2} - j\frac{r_L^2\omega c_L}{1 + r_L^2\omega^2c_L^2}$$

and the phase angle ϕ of the current and grid-filament

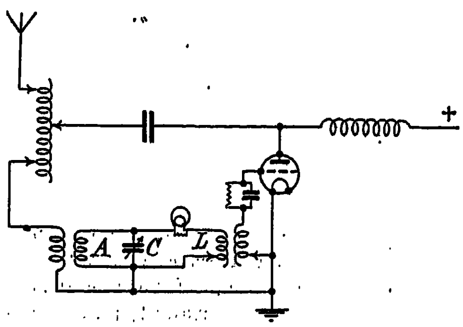

FIG. 21.

voltage, with respect to the voltage across the condenser C_g, is

$$\text{Arc tan }\phi = \frac{r_L^2\omega c_L}{r_1(1 + r_L^2\omega^2c_L^2) + r_L}$$

(neglecting the grid-filament capacity, which is usually negligibly small).

The effect of this phase angle ϕ is given in the vector diagram (Fig. 20). The current i_{Lg} is the vector sum of the currents i_g and i_1, and the induced E.M.F. ωMI_1 is at right angles to the oscillatory current I_1. For normal anode tapping, the anode tapping voltage V_1 is approximately at 90° to I_1, and so also is the anode condenser current i_a. The anode condenser P.D. v, when added to V_1, gives the valve anode voltage V_a. The valve current is i_v and the anode choke current i_b.

For the case of a large value of the angle ϕ corresponding to a small value of r_1 the effect may be a considerable variation from phase opposition for the anode and

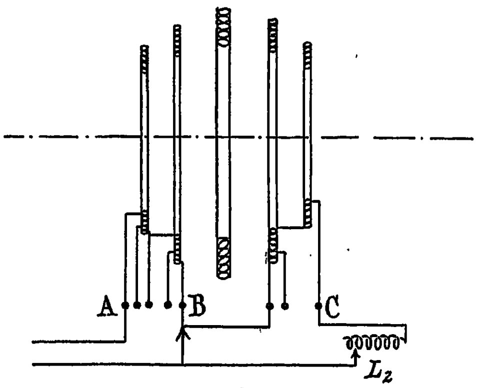

FIG. 22.

grid oscillatory potentials V_a and i_1r_1, respectively, resulting in a loss of efficiency. This condition may occur when a considerable number of valves are being arranged in parallel, especially for the case of a common grid-leak

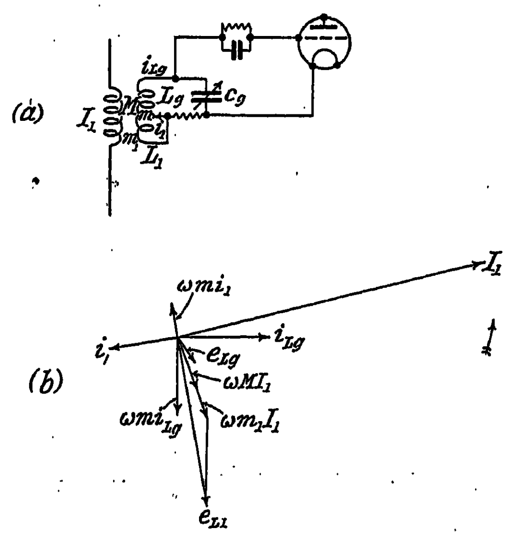

FIG. 23.

resistance and capacity; in this case separate grid leaks are usually better for efficient working. To a certain degree this de-phasing may be avoided by re-adjustment of the grid tuning condenser C_g if a resistance r_g is present, in which case the increase of the current i_{Lg} with increase of the condenser C_g gives an increased resistance P.D. $i_{Lg}r_g$ and so brings ωMI_1 more

nearly in phase with i_1r_1. This has the effect that V_a approximates more closely to phase opposition with i_1r_1. There is, however, a limiting condition beyond which this effect cannot be utilized.

As regards the actual value of the grid-filament resistance, this is such that the grid-filament current in practice is closely proportional to v_g^2 for positive values of v_g, i.e. the resistance is proportional to $1/v_g$. Provided that the grid-filament current i_1 when the grid is positive is not too large in comparison with i_g, the grid-filament oscillatory potential will closely follow a sinusoidal

case of a large number of valves in parallel, with resulting low impedance.

The cramped space available for grid coils caused a change to be made from cylindrical to disc coils. The grid coil had to be designed with tappings for a wide range of wave-lengths, and it was necessary to short-circuit the remaining turns when less than the total number were in use, in order to reduce the maximum coil potential and so avoid sparking; with the use of added resistance in the grid condenser circuit the danger of burning out the remaining turns was avoided.

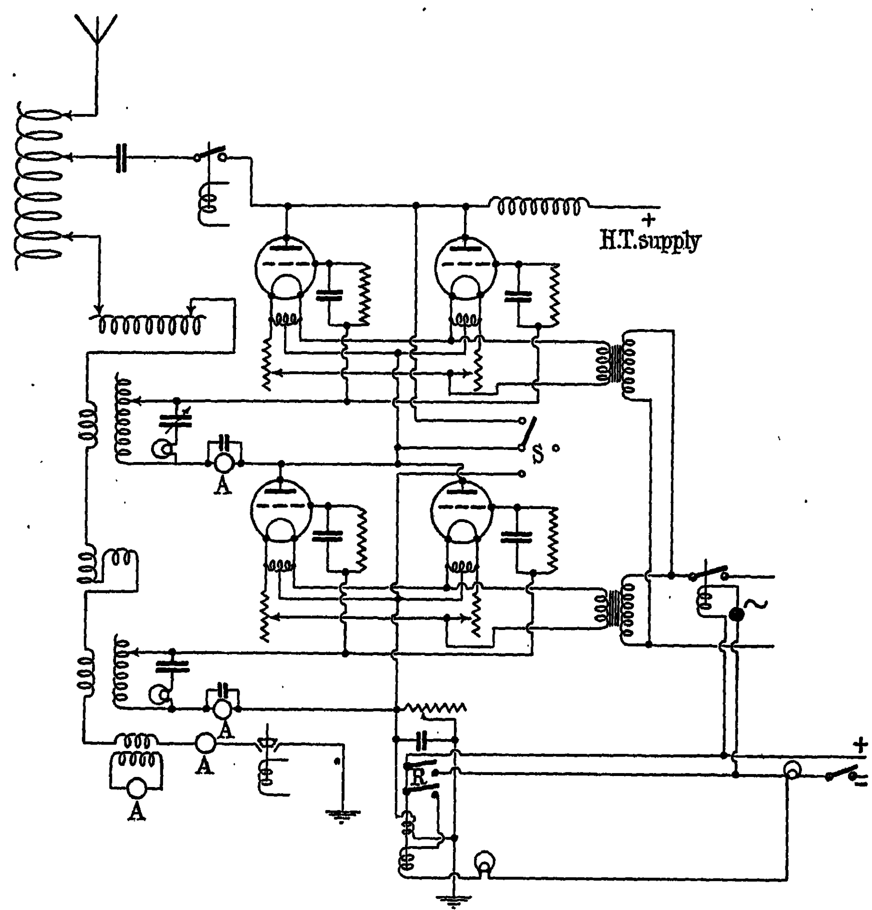

FIG. 24.

wave-form. For cases where this grid current is excessive, due to incorrect adjustments of the grid circuit, the effect may be to reduce the amplitude of the positive loop of grid potential.

For the case of a very low anode tapping, the ratio inductance/resistance for the inductance between anode tapping and earth may decrease considerably; this may cause a phase displacement of current i_a relative to the anode tapping voltage V_1, with resulting loss of efficiency. Usually, however, the best anode tapping for maximum oscillatory current is reached with a higher tapping than that at which this de-phasing occurs, due to the limitation imposed by impedance of the transmitting valves, but de-phasing may occur in the

For ship transmitters giving increased aerial powers of from 7 to 10 kW it has been essential for minimum adjustments over a wide range of wave-lengths to work with coils with no space adjustment, and it was found that if single coils were extended to meet the case, excess voltages and currents were induced in the remaining turns when short-circuited; also on certain wave-lengths the oscillatory current was unstable.

This effect is liable to occur on the shorter wave-lengths, as may be seen from the vector diagram shown in Fig. 23 (*b*) for the circuit indicated in Fig. 23 (*a*). For the current vectors I_1 and i_{Lg} the induced E.M.F. in L_1 will be the vector sum of the E.M.F.'s $\omega m i_{Lg}$ and $\omega m_1 I_1$, i.e. e_{L1}, the current i_1 will be at 90° to the E.M.F.

e_{L1}. The induced E.M.F. e_{Lg} in L_g will be the resultant of ωMI_1 and ωmi_1 and this value may become very small, with resulting instability of the aerial oscillatory current.

The use of multiple-disc coils together with an external inductance L_2 has overcome the difficulty. The former are placed symmetrically on each side of the aerial coupling coil as shown in Fig. 22, and the remaining turns are closed through the external inductance L_2 of suitable value. This reduces the mutual induced E.M.F. ωmi_{Lg} in the inductance L_1 due to reduction of mutual coupling. Further, the current i_1 is reduced in value by the additional inductance L_2 which constitutes a compromise between open-circuit and short-circuit conditions, with corresponding reduction of the mutual E.M.F. ωmi_1. In this way instability of operation on the shorter wave-lengths has been avoided and coils of this arrangement have been designed for a range of wave-lengths from 450 to 5 000 m. The use of discs of different diameters enables the connections to be made readily with no danger of sparking to adjacent turns at higher potentials.

The curves of Fig. 19 show that the variable grid condenser makes only partial use of the resonating properties of the grid circuit, as the phase angle is not far removed from 90° for the grid potential oscillations. Fig. 21 indicates how the correct phase conditions are obtained by the use of a grid oscillatory circuit which is in resonance with the aerial. The induced E.M.F. in coil A from the oscillatory circuit constitutes a supply to the circuit CL which is in parallel resonance with the oscillatory circuit, while the grid circuit is inductively coupled to the inductance L of this circuit. It is possible to operate such a circuit over a wide range of wave-lengths by adjusting the LC values of this circuit alone. This circuit can also be calibrated as a wavemeter, using a low-voltage lamp as indicator. Further, the resonating circuit can be readily modulated for radio telephony by grid potential control.

As regards the grid leaks used with these transmitters, experience has shown that for valves in parallel a separate grid leak for each valve is preferable. With the use of a grid leak common to a number of valves there is danger of short-wave oscillatory currents circulating in the valve inter-electrode capacities and the wires joining the grids to the grid leak. In certain cases the internal leads for grid and anode of the valve have been known to become red-hot due to circulating currents of very short wave-length, although this effect may be avoided by the insertion of resistance in the grid lead, as shown, for example, in the multiphase circuit of Fig. 16.

Series arrangements.—Increased efficiency results from operating the valves, both transmitting and rectifying, at maximum anode voltage. This voltage is limited to the value, in practice, above which there is a danger of blue glow occurring in the valves.

During the period 1918–19 in the naval service the maximum anode supply voltage for average glass transmitting valves in parallel, for an anode dissipation of 500 to 800 watts per valve, was of the order of 7 000 to 8 000 volts.

In order to obtain increased power at these lower voltages it was necessary to employ a large number of valves in parallel with rectifiers designed for low internal resistance and high filament emission. Whilst the experimental design of larger valves suitable for higher voltages was being pushed forward it was obvious that considerable time would elapse before such valves would be available in quantities, and another factor for consideration was the existing h.t. transformer plant which in many cases gave normally secondary voltages to earth of from 15 000 to 20 000 volts.

Experimental trials of valves in series were made during 1919 as shown in Fig. 13, the filament system of the upper valve being at a high-frequency potential to earth. With this arrangement it was found possible to operate at a supply voltage approximating to twice the safe value for a single valve, with the valve anodes at normal full-power dissipation. If we consider the case of valves in parallel, it is necessary, as the number in parallel is increased, to lower the anode tapping point in consequence of the reduction of valve effective impedance. With decrease of the inductance between anode tapping and earth to a small value, and depending on the aerial resistance, there may be a decrease of efficiency for the best aerial current position. Referring to Fig. 17, this is due to the anode condenser current i_a becoming displaced from a phase angle approximating to 90° to the oscillatory current I_1 and so resulting in an increase of the value of i_a, and therefore of the valve current i_v (with increased valve heating) relative to the current I_1. For such a condition it is advantageous to operate with valves in series employing a higher anode voltage and higher anode tapping. The normal advantage of the series system as regards efficiency is obtained, however, when the anode supply voltage is greater than that which can be applied with safety to a single valve. A further advantage is the reduction in the rectified current for a given rectified power, with resulting increase of rectifier efficiency.

The arrangement has proved to be very stable in operation, and no direct short-circuit to earth is caused in the event of failure of one valve, as is the case with valves in parallel. For the case of valves with open grids the insulated grids of the upper valves prevent excessive valve current if, for any reason, failure of the aerial oscillatory current occurs.

A typical circuit diagram for such a set is given in Fig. 24. The filaments for the upper bank of valves are supplied from a transformer with oil insulation which can be designed readily for high-frequency voltages between primary and secondary windings and have small capacity between windings. The grid coupling coil for the upper bank of valves has to be insulated from its aerial circuit coupling-coil for the high-frequency voltage across the lower bank. Separate filament rheostatic control enables equal division of the voltage across the valves to be obtained.

A number of sets of this type were designed early in 1920 for use with transformer plant already installed, and one set employing six silica valves (three valves in each bank with two banks in series) has been in use at Horsea for routine and experimental work since May 1920.

Coupled circuits.—The small space available in ships for the transmitter has necessitated the employment largely of plain aerial circuits for normal full-power transmissions. Provision has been made, however, for the introduction of a steadying circuit for drying-out if for any reason the aerial insulation is liable to short-circuit by salt water or spray. For wave-lengths below 600 m there is usually no difficulty in starting up under wet conditions. A coupled circuit is usually employed,

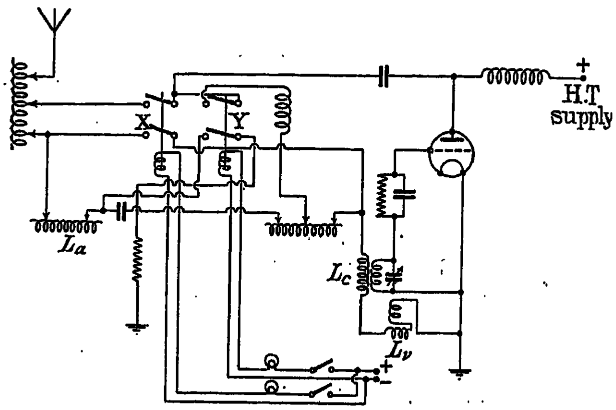

FIG. 25.

however, on these shorter wave-lengths to obtain the necessary constancy of wave-length for the highly selective valve transmissions.

In many cases use has been made of a resistance-coupled circuit. Alternatively, the more usual electro-magnetic coupling has been employed. To enable the change from plain to coupled circuit on the same wave-length to be readily made when required, switching

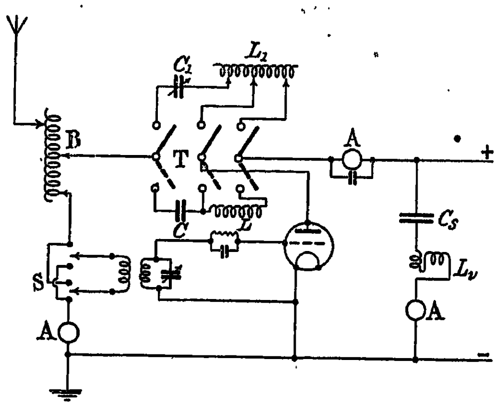

FIG. 26.

arrangements may be employed as shown in detail in Fig. 25. With the contacts of switch X closed, the normal oscillatory circuit is in use, and with the contacts of switch Y closed, the aerial circuit is resistance-coupled to a local circuit which is so adjusted that the wave-length transmitted is practically the same in the two cases. This is effected by arranging for the introduction into the aerial circuit of the inductance L_a of value equal to the sum of L_c and L_v transferred to the local circuit when the switch Y is closed.

The resistance employed for drying-out is that value for maximum product of local current and resistance with aerial earthed. The effectiveness of the drying increases rapidly with decrease of wave-length.

An alternative circuit which has been employed in certain cases for C.W. transmissions is shown in Fig. 26, in which the anode circuit C_1L_1 together with the smoothing condenser C_s and inductance L_v is tuned to the value of the aerial LC. The anode condenser C_1 is of small value and has a high-frequency P.D. which approximates to twice the value of the P.D. between anode tapping point B and earth; as a result, the valve anode potential oscillations are in phase opposition to the anode tapping P.D., and the grid coupling coil has to be reversed in direction by means of the switch S if, as in Fig. 26, the circuit is changed from the plain aerial circuit CL for normal transmissions to the tuned anode circuit C_1L_1 for drying-out by means of the change-over switch T. Exact tuning of this circuit can be readily provided for by placing in the earth lead of the smoothing condenser C_s a fine-adjustment inductance L_v of small value. The step-up current ratio can be of the order of 5 : 1 or 7 : 1 so that the size of the anode inductance and condenser is relatively small; the space occupied for a given power

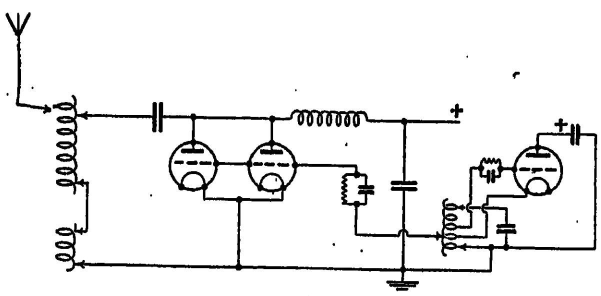

FIG. 27.

is considerably less than for the coupled circuits of Fig. 25.

Separate grid excitation.—Circuits employing separate grid excitation have been developed for use with medium-power and high-power valve transmitters. It has been usual to connect the grids of the main transmitting valves directly to the local oscillatory circuit, as shown in Fig. 27. For best operation at varying power it is desirable to arrange for proportionality between the grid exciting current and the main-supply anode voltage, having once adjusted the grid voltage to give best efficiency for a given anode voltage. A rectified a.c. supply for C.W. transmission can be arranged by supplying the exciter from a small transformer the primary of which is connected in parallel with the main transformer.

Comparative experiments have usually given a higher efficiency for this circuit than for the retroactive circuit, assuming proper adjustment of the grid exciting voltage. The fact that the grid is initially excited also renders the circuit more stable in operation, especially for the case of a low anode tapping, and the circuit has been found slightly more effective than the retroactive circuit for starting-up aerial oscillatory current when the aerial insulation is partially short-circuited by

moisture. The superiority of this circuit as regards constancy of wave-length is shown by the experimentally determined curves of Fig. 28, which also illustrate the rapid fall in oscillatory current with change of aerial tuning. For the case of ships' aerials, variations in wave-length of the order of 0·4 to 0·5 per cent have been observed with retroactive coupling during rough weather conditions for wave-lengths of the order of 2 000 m. From the curves it will be seen that these variations correspond to a reduction of aerial current by 30 per cent of its best value for the separately excited grid circuit, but for reception the change of intensity of received note arising from this is preferable

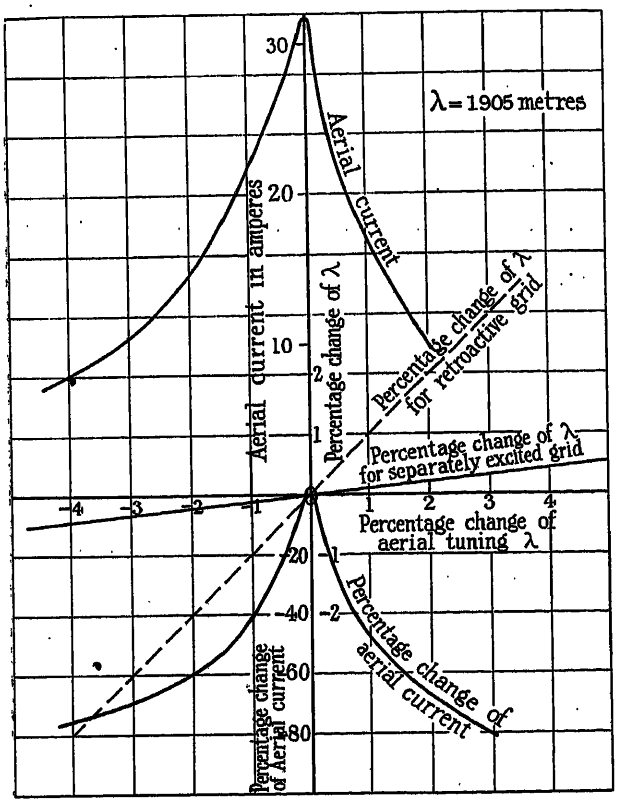

FIG. 28.—Change of λ for separately excited grid.

to the alternative of change of note with retroactive coupling.

The power supplied to the local oscillator circuit must be such that it will readily supply the power required to set up the necessary grid oscillatory voltage without instability of the local oscillatory current for any supply voltage to the main transmitter. The local circuit must also be so screened from, or at such a distance from, the main oscillatory circuit that there is no mutual inductive coupling. In addition, the tapping of the local circuit inductance at which the grid tapping point for the main valve is made must be such that there is no tendency for the main transmitter to set up oscillatory current by virtue of the valve capacity from anode to grid and the inductance from grid to filament of the local circuit, otherwise variations of wave-length will occur with change of the aerial capacity or inductance. This adjustment can be determined by trial for a given wave-length, or, alternatively, an additional resistance of small value may be used in the lead from grid to grid leak to minimize this effect. The best results have been obtained in practice by so arranging the grid tapping and adjusting the local circuit current that the inductance in use for suitable grid oscillatory voltage is from one-quarter to one-fifth of the local circuit inductance.

As the only adjustments required for the local circuit of Fig. 27 are those of the oscillatory circuit inductance or capacity, the whole circuit can be readily adjusted to any required wave-length. The space required for the arrangement is not very much greater than that for the ordinary retroactive circuit.

Overload protection of valves.—The supply circuits to the rectifier units have been protected from possible breakdown of circuit insulation by the use of horn-break fuses, and a simple form of overload relay with two coil windings has been fitted in the valve-current circuit for the transmitting valves and designed to operate if, for any reason, the anode current is excessive. The relay contacts short-circuit the bobbin for the main filament switch and so switch off all the valve filaments; at the same time, or slightly earlier, the d.c. supply circuit is completed through the other relay coil in series with a danger lamp. Thus the series lamp in the operating cabinet for the main filament switch bobbin lights up brightly to warn the operator, and at the same time the danger lamp on the set lights up. To reset the relay, all that is necessary is for the operator to break and then remake his d.c. control switch in the cabinet. Adjustment of the relay for any required operating current is provided by an adjustable resistance in parallel with the operating bobbin, which also has a condenser in parallel for the a.c. component of the unidirectional valve current. A relay of this type is shown at R, Fig. 24, arranged to operate in the case of excess current to the transmitting valves.

Alternatively, the relay contacts may be arranged to break either the primary a.c. supply for the transformer or the motor-alternator supply if desired, but in practice no difficulty has occurred when using the convenient arrangement of filament control, as the rectifying valves easily withstand the h.t. line voltage when the valve filaments are cold.

Reduction of harmonic interference.—The main interference caused is directly due to the valve transmitter itself, although interference is to some extent caused by the aerial circuit having distributed capacity and inductance. The valve interference is due to the non-sinusoidal wave-form of the current pulses which circulate in the oscillatory circuit via the anode condenser; more especially is this the case when the valves are operated at high efficiency with their grids at a considerable mean negative potential.

The principal methods which have been employed experimentally are (*a*) the introduction of special circuits in the anode tapping circuit to act as harmonic filters, (*b*) the use of special circuits (either acceptor or rejector in type) in the aerial circuit, and (*c*) the use of intermediate circuits coupled to the aerial.

In the case of methods (*b*) and (*c*), condensers and

inductances are required sufficient to carry for (*b*) the aerial oscillatory current and, for (*c*), currents which may be equal to or greater than the aerial current. These inductances are naturally expensive and occupy considerable space.

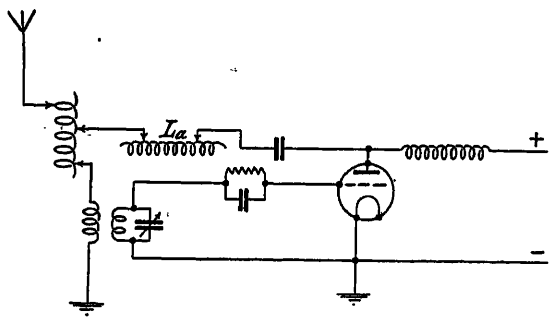

FIG. 29.

Experiments were made during 1920 with method (*a*), using a series inductance L_a between the anode condenser and anode tapping point to form a circuit from the valve anode tuned to the aerial LC as in Fig. 29,

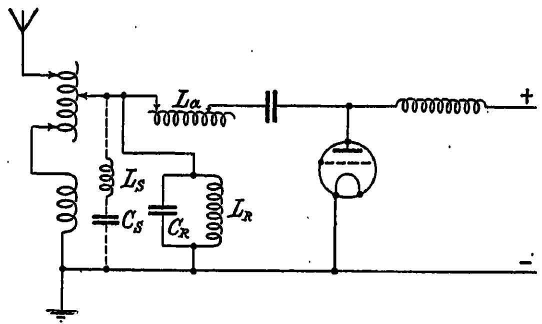

FIG. 30.

so that minimum impedance is offered to the fundamental component of the anode condenser current. These experiments indicated, however, that whilst considerable reduction of the aggregate harmonic power was possible,

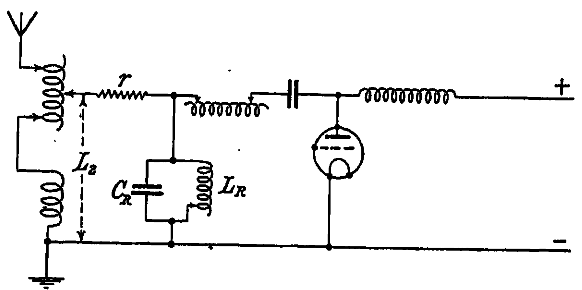

FIG. 31.

a certain harmonic, possibly irregular (depending on the value of the series inductance), was reinforced. If a rejector circuit L_RC_R was added, as in Fig. 30, a particular harmonic was reinforced, depending usually on the LC product of the rejector capacity and the aerial inductance from anode tapping to earth. Similarly it was found that if shunt circuits, such as L_SC_S indicated by dotted connections, were added tuned to particular harmonics, another harmonic was reinforced for the same reason.

The insertion of a resistance r between the anode tapping point and the filter circuits of a value such that the capacity of the rejector or shunt circuit when combined with the aerial inductance formed with the resistance r an aperiodic circuit, i.e. $r^2 > 4L_2/C_R$, was

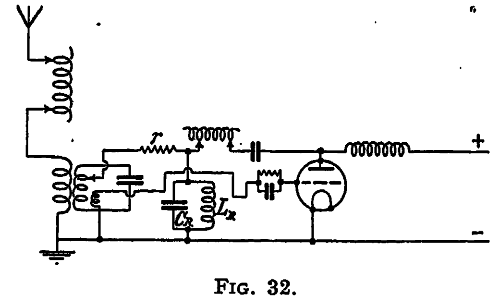

FIG. 32.

found to avoid the above harmonic reinforcement, and the arrangement found most satisfactory is given in Fig. 31. There is now a power loss in the resistance, but the pulsating current is small relative to the aerial current and it is possible to choose the rejector circuit capacity such that the value for r constitutes a loss of

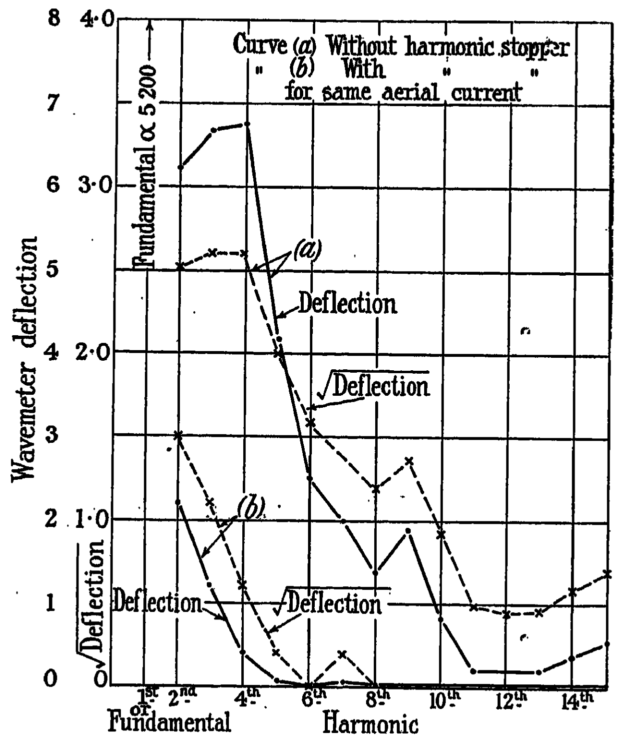

FIG. 33.—Comparative results.

the order of 5 per cent or less of the total oscillatory power. Provided that the circuit L_RC_R is highly efficient, its power absorption will be small.

The largest reduction has been obtained for harmonics above the 5th, and the reduction obtained has been small for the 2nd and 3rd especially. Fig. 33 indicates typical results obtained for the circuit of Fig. 31 by

direct measurement of the harmonics by the use of a wave-meter. For the 2nd and 3rd harmonics a greater reduction has been obtained using the ordinary coupled circuit, and the best results have been obtained by combining the filter circuit of Fig. 31 with either an intermediate coupled circuit (inductively coupled as in Fig. 32 or, alternatively, employing capacity coupling), or with a double-acting type of circuit in which the even harmonics are reduced by being set up in phase

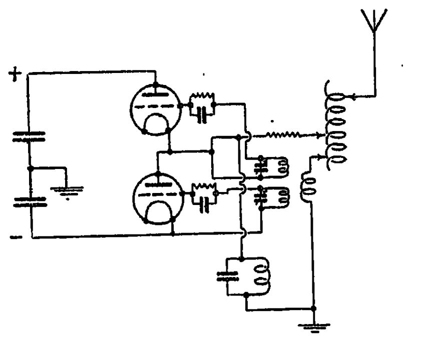

FIG. 34.

opposition for the two halves of each high-frequency period, as in Fig. 34. In addition, the valves must be operated at the minimum negative potential consistent with good efficiency.

Signalling arrangements.—For sets handling powers of the order of 20 to 30 kW and operated at hand speeds, primary-supply circuit control has been employed. For higher powers either h.t. keys in the transformer

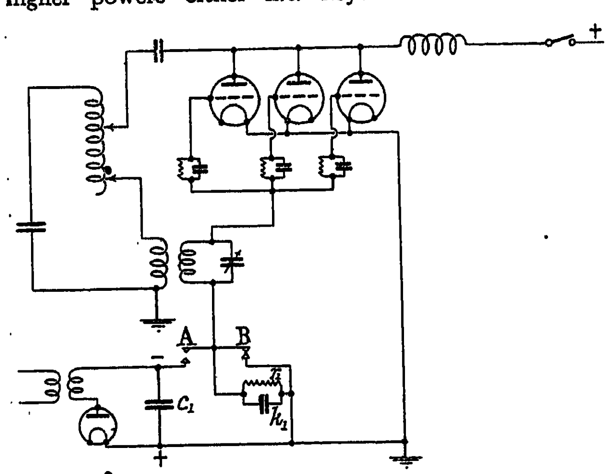

FIG. 35.

lines or anode supply, or grid potential control, have been employed. For the case of valves with separate grid leaks, it has been usual to employ a key in the common grid-filament lead operating across a resistance r_1 and condenser k_1, as in Fig. 35, a suitable negative potential being obtained from the condenser C_1 which is charged from a small rectifier unit as shown; this has been applied to control aerial powers of the order of 30 to 40 kW at speeds up to 150 words per minute, the aerial current being reduced to zero, or nearly so, depending on the value of the negative potential introduced across the resistance.

The resistance r_1 and condenser k_1 have such values that initial shutting down of the oscillatory current occurs when the contact B of the key is opened, and with suitable adjustment of the negative potential across condenser C_1 it is possible to work with very little sparking at the contacts A and B.

Other methods utilizing a 3-electrode valve as grid leak and signalling by the introduction of a negative potential from grid to filament of this valve have also been employed.* As listening-through is practically universal for all naval valve sets, methods of signalling by marking and spacing waves are not usually employed except in experimental cases. In the case of signalling by grid potential control, the rectifying valves have to withstand the full no-load potential of the a.c. supply; on the other hand, with primary circuit signalling there are intermittent electrostatic forces on the electrode system and care has to be taken that no mechanical resonance effects are set up, especially on the filament.

Design of transmitting valve electrodes.—The following method has been used for estimating the main dimensions of the electrode system when the grid is run at a considerable mean negative potential.

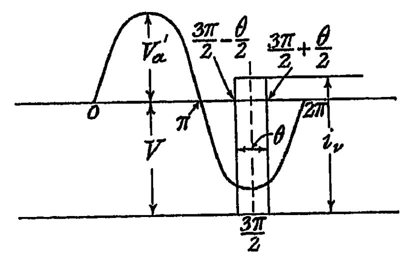

FIG. 36.

Consider the case of the circuit of Fig. 17 and assume that the anode oscillatory potential is sinusoidal, as indicated in Fig. 36.

Let V_a' = amplitude of anode oscillatory potential;
V = supply d.c. voltage;
W = d.c. power supply ($I = W/V$);
V_g' = maximum grid positive potential.

The valve has to carry maximum current for the anode-filament P.D. of $V - V_a'$.

The quantity through the valve per period of time T is IT.

This quantity passes through the valve for a fraction of the period considerably less than $\frac{1}{2}T$. As regards the wave-form of the valve current, since the anode potential is decreasing with increase of grid potential the resultant tendency is to maintain fairly constant anode current for the major portion of the time when the grid potential is positive. In addition, as already pointed out, the tendency of the grid-filament current is to limit the amplitude of the positive loop

* The use of a valve as grid leak for signalling has also been developed by the Royal Aircraft Establishment, Farnborough, without the use of a negative potential, the oscillatory current being set up by the use of a key joining grid to filament of the grid-leak valve. Also see paper by Lieut.-Col. A. G. T. Cusins: *Journal I.E.E.*, 1922, vol. 60, p. 246.

of potential. For these reasons a rectangular waveform of valve current for the angle θ corresponding to the time for which current flows is a fair approximation. The value of the angle θ will depend on the grid circuit and for the case of the circuits in use of the inductive coupling or separate excitation type it is usually of the order of $\frac{1}{2}\pi$ to $\frac{2}{3}\pi$.

The valve current $i_v = 2\pi I/\theta$.

The valve energy loss per period

$$= \frac{T}{2\pi} \cdot \frac{2\pi I}{\theta} \int_{(3\pi/2) - \frac{1}{2}\theta}^{(3\pi/2) + \frac{1}{2}\theta} (V + V_a' \sin \alpha) d\alpha$$

$$= IVT \left(1 - \frac{V_a'}{V} \cdot \frac{2 \sin \frac{1}{2}\theta}{\theta}\right)$$

The efficiency $\quad = \dfrac{V_a'}{V} \cdot \dfrac{2 \sin \frac{1}{2}\theta}{\theta}$

The energy given to the oscillatory circuit

$$= IVT\left(\frac{V_a'}{V} \times \frac{2 \sin \frac{1}{2}\theta}{\theta}\right)$$

As an example, assume the following :—

Supply power = 30 kW at 12 000 volts; $\theta = \frac{1}{2}\pi$ and $V - V_a' = 0 \cdot 2$ volt.

The efficiency $= 0 \cdot 8 \times \dfrac{2/\sqrt{2}}{\frac{1}{2}\pi} = 71$ per cent.

The supply current $I = 30/12 = 2 \cdot 5$ amperes.

The valve current $i_v = 2 \cdot 5 \times \dfrac{2\pi}{\frac{1}{2}\pi} = 10$ amperes.

The valve filament must be designed for this emission, also, in addition, to carry the superimposed electron current without excessive filament heating, and supply the grid-filament current during the positive grid oscillatory period.

It is usual to design the filament for 50 per cent greater emission current than the above value at a temperature between 2 450° and 2 500° K., i.e. the required electron current = 15 amperes.

The maximum grid oscillatory voltage should be less than the anode-filament voltage for maximum valve current; its value will be assumed to be about 1 500 volts, and a moderately close grid will be assumed of $m = 200$.

The valve grid diameter d' must be such that

$$i_v = 2 \cdot 93 \times 10^{-5} \times \frac{l_f}{\beta^2 d'} \left(\frac{V - V_a' + mV_g'}{m + 1}\right)^{3/2} *$$

(where l_f = effective length of filament)

$$= 2 \cdot 93 \times 10^{-5} \times \frac{l_f}{d'} (V_g')^{3/2} \text{ as an approximation.}$$

Also, for the anode diameter d_a relative to the filament,

$$i_v = 2 \cdot 93 \times 10^{-5} \times (V - V_a')^{3/2} l_f / d_a$$

Hence $\quad \dfrac{d_a}{d'} = \left(\dfrac{2\,400}{1\,500}\right)^{3/2} = 2 \cdot 03$

* B. S. Gossling: *Journal I.E.E.*, 1920, vol. 58, p. 676.

If for a loop filament (where l_f = effective axial length of loop), the value of d' is, for mechanical reasons, 5 cm.

Then the anode diameter should be not greater than $5 \times 2 \cdot 03$ (say 10 cm). For this diameter

$$l_f = \frac{i_v \times 10^5 \times 10}{2 \cdot 93 \times (2\,400)^{3/2}} = 29 \text{ cm}$$

The anode will have an area of $10 \times \pi \times 29 = 910$ cm. The anode power dissipation is $30 \times 0 \cdot 29 = 8 \cdot 7$ kW and this area of anode (if of molybdenum) is ample for the power dissipation required during static bombardment. The case of the valve being operated at full power at reduced supply voltage and efficiency will also be covered, e.g. if the valve is operated at 10 000 volts, and efficiency say 60 per cent, the anode dissipation is 12 kW.

If such a valve is bombarded during exhaustion to, say, about 70 to 100 per cent greater power than the maximum dissipation power, i.e. say 20 to 24 kW, this will provide a reasonable factor of safety for normal use at anode potentials up to 12 000 volts. In this connection it is desirable to specify a reasonable time of bombardment at full power, as in certain cases valves which are bombarded for a short time sometimes fail after continued use at full power, probably due to continued heating of the cooler parts of the valve.

Valve rating.—Reference to the above indicates that the geometry of the valve has a higher degree of importance than the anode power rating. This has been already pointed out by other writers.* For the valve manufacturer it is essential to specify a given anode power for static bombardment of the valve, and acceptance tests, but this may not necessarily represent the safe anode power dissipation for oscillatory conditions in which other limits are :—

(1) Maximum permissible oscillatory voltage between (*a*) anode and filament, (*b*) anode and grid, and (*c*) grid and filament.

(2) Maximum possible current through the valve at the specified minimum anode-filament voltage, without filament saturation. This depends on the geometry of the electrodes as well as on the filament.

For these reasons it is usual to specify the valve as capable of handling so much supply power at a given efficiency and to specify to the valve manufacturer a bombardment power giving a reasonable factor of safety; for example, for the case of a valve the anode of which is to be bombarded to 30 kW during exhaustion, if we allow 60 per cent as the minimum operating efficiency, the oscillatory rating of the valve for a factor of safety of 2 would correspond to a supply power of 37·5 kW and an aerial power of 22·5 kW. Efficiencies of the order of 60 to 70 per cent are readily obtained in practice, but higher efficiencies obtained by increasing the grid negative potential may result in a considerable increase of harmonics.

Size of valve units for a given output.—With increase of the power output from a transmitter there has been progressive increase in the size of the valve unit to

* See, for instance, E. H. Shaughnessy: Address to the Wireless Section, *Journal I.E.E.*, 1924, vol. 62, p. 51.

avoid complexities of circuit connections which would otherwise be necessitated by the employment of a large number of valves in parallel.

The larger unit also results in the saving of space with improved operation efficiency. It has been usual to employ not more than three valves in parallel for aerial powers up to 60 kW, these valves being capable of handling a supply power of 90 kW, and, for still higher powers, arrangements of six valves in series-parallel (three valves in each bank with two banks in series) are being employed. The use of the larger unit for these various groupings avoids excessive complexity of valve connections, and, in the event of failure of a valve, there is usually a sufficient reserve of power to tide over the emergency.

To meet these requirements the silica valve* was developed during 1919–1920 in three main sizes, namely for supply powers of 5 kW, 9 kW and 20 kW. More recently, single valves have been designed for supply powers of 30 kW and 60 kW at an anode supply of 12 000 volts. For supply powers up to 30 kW the valve seals and envelopes have been cooled by air ventilation, but for these or higher powers water cooling may be employed. Table 2 gives some of the main electrode dimensions of standard types of valves.

TABLE 2.

Transmitting Valves.

Valve	Filament			Grid		Anode		Supply			Aerial power	Static bombardment during exhaustion
	Voltage	Current	Power	Diameter	Calculated $m=\frac{dv_a}{dv_g}$	Diameter	Length	Voltage	Current	Power		
	volts	amps.	kW	cm		cm	cm	volts	amps.	kW	kW	kW
NT23	16·0	14·3	0·23	2·75	24	7·0	8·75	9 000	0·7	6·3	4·4	3·0
NT24	17·5	29·0	0·51	3·0	210	8·0	12·0	10 000	1·0	10·0	7·1	4·5
NT22	29·5	50·0	1·47	5·0	410	12·5	27·5	12 000	2·6	31·0	21·0	20 to 25

The paper is published with the permission of H.M. Admiralty. The author desires to express his thanks to the Captain, H.M. Signal School, for assistance in the preparation of the paper. He is greatly indebted to Mr. H. Morris-Airey, C.B.E., M.Sc., the Chief Technical Adviser, H.M. Signal School. He also desires to acknowledge the ready co-operation and assistance of members of the Signal School staff in the experimental work, particularly of Mr. E. J. Grainger, M.Sc., Mr. C. Matthews, Mr. H. R. Cantelo, B.Sc., and Mr. J. E. Sheldrick, B.Sc.

* Described by H. Morris-Airey in a paper read before the Wireless Section, 7th March, 1923.

Discussion before the Wireless Section, 3 December, 1924.

Professor C. L. Fortescue: Having been intimately connected with the early work forming the basis of the developments described in this paper, it is interesting to me to look back and to see how the many difficulties have been overcome. It has been mainly a matter of increasing the size of the valves used, combined with careful detail improvements. The increased power has enabled the difficulties arising from what the author naïvely describes as "severely wet conditions" to be overcome without risk of damage to the valves, which was perhaps the most serious obstacle encountered in the early days. With regard to the method of calculating the performance of the rectifier, this can be done from the 3/2-power law for unsaturated filaments by a method which seems quite as accurate as that adopted by the author. The general results are the same as for the case of the saturated filament, but the efficiency is higher in a properly designed valve, as was well known in 1918. With regard to Fig. 19, the protection offered by the addition of 180 ohms in the grid circuit seems to be scarcely as much as the author suggests. It appears, in fact, to make the conditions somewhat worse and renders protective devices still more necessary. The six-phase method of working shown in Fig. 16 gives good results when properly adjusted, and the amplitude of the resulting oscillation is as constant as that given by most sets employing two-way rectifying units and a single-phase supply. The author's method of calculating the performance of the oscillating valve from the curves of Fig. 36 is only very approximate. Many working conditions differ widely from this and results calculated in this way may be quite misleading unless based directly on closely similar experimental observations. Finally, the author's claim that the rating of the valve is less important than the electrode design is one which requires careful consideration. In practice the efficiency must be limited by the harmonics generated and, unless the valve can safely dissipate the losses, failure is inevitable. With regard to the electrodes, however, considerable variation can be compensated for by circuit adjustment, and consequently some latitude can be allowed to manufacturers.

Mr. L. Grinstead: In connection with the data concerning rectifying valves I should like to draw atten-

tion to the three items which the author gives as determining the design of the valve. Whilst items (*a*) and (*b*) are perfectly clear, the definition of (*c*) is rather vague. The author states "the maximum anode-filament valve P.D. with anode positive." Can he give any reason why the particular figure of 3 000 has been chosen, and what limits there are in practice within which one can depart from that value? Could that figure be greatly varied in the case of a valve worked over the saturation bend? The circuit arrangement shown in Fig. 24 is an interesting type of circuit design used in the Signal School which employs valves in series, and it is remarkable to me that it has been possible to obtain a filament transformer dealing with a fair amount of power which can be placed in the circuit, since this has to withstand not only half the high-tension voltage to earth, but also practically half the radio-frequency potential. The author gives some interesting information about separate grid excitation. Can he give some idea of the size of the valve which feeds the grid circuit of the main valves supplying the aerial? Is there any definite relationship between the rating of this to the main valves, and how much latitude is there in this respect? I am inclined to agree with Prof. Fortescue that the actual design of the valves, provided it is scientific, can be varied over very wide ranges. The question of the grid design, of course, does enter to some extent into the two conditions given in limit No. (2). During oscillation the anode voltage is actually a minimum, when the anode current is a maximum, and if the grid is too "close" it will be impossible to pass the necessary current to maintain the output. At the end of the paper the author gives some interesting data in regard to the large silica valves which are now made. At present the largest commercial valve is of the order of 30 kW input, and it would be interesting to know the probable limiting size.

Mr. R. V. Hansford: My very mild criticism is that I do not think the author has made sufficient distinction between experimental work and practice; that is, the paper gives a record of experiments made with circuits and apparatus, but we are not sure which have been adopted and become the standard practice of the Admiralty. The paper would have been even more interesting if the author had drawn further on his practical experience and given us some idea of the *relative* advantages of the various circuits. As examples I should like to refer to the two important questions of grid excitation and harmonic interference. Experience in the Post Office indicates that the method of separate grid excitation is much better than self-excitation for medium-power and high-power transmitters. It brings with it the great advantage of constancy of frequency to which the author refers, but also the disadvantages that variation in the aerial not only reduces the aerial current but may produce undue voltage strains on the valves themselves on account of the variation in the impedance of the associated circuits if a sufficient factor of safety is not provided. (Incidentally the text does not seem to be quite in accord with Fig. 28. Does a variation of 0·4 per cent of aerial capacity really reduce the aerial current to 30 per cent of its normal value?) Is it now the normal Admiralty practice to design a set of medium power with separate excitation on the grid? On board ship a difficulty, of course, is the small space available, but this would not apply to the case of a land station. With regard to harmonic interference, I should be interested to know whether harmonic stoppers are now normally fitted (1) on ships, and (2) on land stations. In the section of the paper which deals with harmonic interference, the author has a sentence which reminds me of a patent specification in the sense that it seems

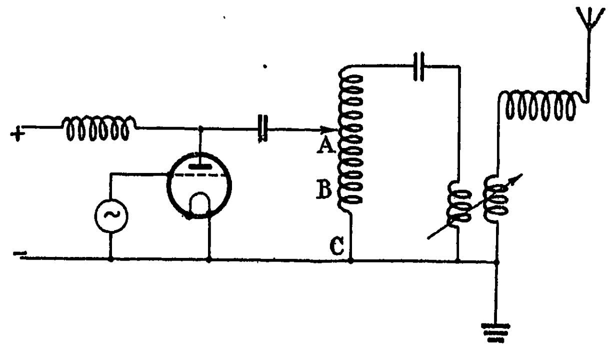

Fig. A.

to have been put in to be sure that everything is covered; it is as follows:—"The best results have been obtained by combining the filter circuit of Fig. 31 with either an intermediate coupled circuit (inductively coupled as in Fig. 32 or, alternatively, employing capacity coupling), or with a double-acting type of circuit in which the even harmonics are reduced by being set up in phase opposition for the two halves of each high-frequency period, as in Fig. 34." I should like to know which of the many possible combinations included in this comprehensive statement the author really does consider to be the

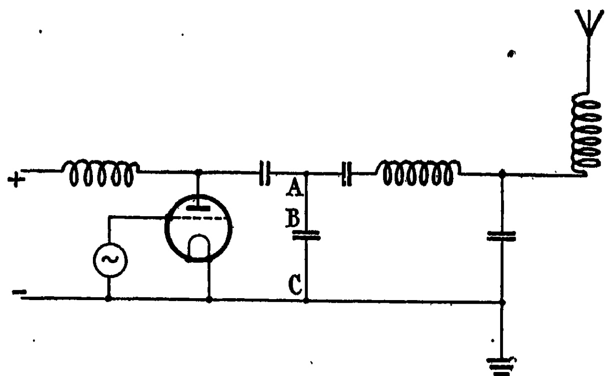

Fig. B.

best, because, of course, within the brackets he has given two alternative methods which are vastly different as regards efficiency in the reduction of harmonics. It seems to me that all the circuits given in the paper show a tendency to use inductive reactance where capacitative reactance would be preferable. Most of the circuits given in the paper are included in the general skeleton diagram of Fig. A with an inductive anode tap. Now we can equally well use a capacitative anode tap as shown in Fig. B. The impedance of path ABC in

Fig. A to the fundamental is the same as the impedance of the path ABC in Fig. B. The impedance of path ABC in Fig. A to the nth harmonic is, however, n^2 times that of path ABC of Fig. B and it is fairly clear (by inspection) what can be proved mathematically if it be assumed that the wave-form of the feed current is constant, viz. that a circuit with a capacitative anode tap is about n^2 times better in respect of harmonic emission than one with an inductive anode tap. The same argument applies to the coupling to the aerial circuit, so that the complete circuit of Fig. B. is roughly n^4 times better, as regards harmonic interference, than that of Fig. A. I suggest that these differences which the author has coupled together in a parenthesis are more important than the use of harmonic stoppers. I think also that if the grid coupling were capacitative, the difficulties of phasing referred to in the paper would probably be reduced, but I assume that questions of space and range of wave-length required would prohibit the general use of capacitative reactances for Naval circuits. The author says that it is usual to employ not more than three valves in parallel for aerial powers up to 60 kW, and for still higher powers a series-parallel arrangement. I should like to ask whether the Signal School does actually provide a regular wireless service in which three valves give 60 kW in the aerial. It is a splendid performance if that is the case, but of course it is one thing to do this for a short period of test and quite another thing to provide a regular service, with the necessary factor of safety not only on the anode dissipation but on the voltages which the valves will withstand. The series arrangement of valves was no doubt a desirable expedient under war conditions when it was necessary to use a particular voltage supply for a particular type of valve which would not withstand more than a certain voltage; but I presume that the author would not recommend a series-parallel arrangement for a new design under present circumstances. He says that such an arrangement avoids an excessive complexity of valve connections. I should have thought, on the contrary, that to place banks of valves in series would have added to the complexity, and I can see no compensating advantages.

Mr. B. S. Gossling: I am inclined to join issue with Prof. Fortescue in his criticism of the author's approximate calculations. It is certainly true that in the case of the rectifier valves the calculation could have been worked out as Prof. Fortescue has suggested, but I am not at all sure that the author's method may not have been equally good even in that case, and I think that his method of handling the three-electrode case mentioned towards the end of the paper is very satisfactory. There are so many variables to keep in mind—one has only to look at Table 2—and the author's method of getting clearly in mind what are the essentials of the problem and trying to combine those essentials into a relatively simple formula is likely to be a great help to those engaged in this work. When treating of the characteristics of the valve in relation to its efficiency as an oscillator, the author might have taken the full equation of the characteristic curves and have tried to find a mathematical approximation to them which would give him something that could be worked out, but the result is not likely to be so manageable as the simple formulæ given at the end of the paper. Although they contain assumptions the author does at least state where these occur. It is good to combine as much as possible of the essentials into a few simple formulæ so that one can get an approximate solution in a reasonable time and know where the pitfalls are. To take a case in point, the author makes assumptions about the average conditions under which a valve oscillates and then he says finally that it is usual to design the filament with a 50 per cent margin in emission. This statement interested me because I have actually measured the peak value attained by the valve emission using ordinary operating adjustments of the valve. The author deals with an ideal square-headed curve, while in my case the peak value does prove to be 50 per cent above his average value. I am in no disagreement with the grounds of the author's assumptions—I have these experimental reasons for believing them to be sound—but I should be glad if he would give some indication of the methods by which he has actually measured the minimum of the filament/anode voltage under operating conditions, and the method by which he has measured the maximum grid voltage. These points are absolutely fundamental to the design of the valve, and some indication of simple experimental methods of making those measurements when a set is being tuned up would be very interesting. For instance, it is quite clear that the operator can choose various sets of circuit adjustments which give him the same overall efficiency. Very small changes in the circuit adjustment may make a great deal of difference to the value of the valve current, and it is the value of the valve current that determines the life of the valve. It would be quite possible, if the circuit adjustments are made without paying attention to the variation of the anode voltage and the variation of the grid voltage, to arrive at a circuit adjustment which gives a desired efficiency but takes 50 or 100 per cent greater peak emission and consequently shortens the life of the valve. A simple circuit arrangement enabling these factors (which do not appear on the supply current instrument or the oscillatory current instrument) to be kept in view would be very useful. An obvious point when considering the competition between the valve, the alternator and the arc as alternative generating methods, is the average life of the transmitting valve together with the cost of replacement. Even at present it is true to say that, provided the valve is not of a specially expensive sort and that power is not obtainable at the very cheapest rate, valves can be made to last so long that the cost of replacing a valve by a new one is only of the same order as the cost of the power required for heating its filament during its life and is therefore a very small fraction of the total power bill for the installation during the same period. The author gives the running temperatures of the filaments as 2 450° and 2 500° absolute and as he refers to Mr. Stead's work I take it that these temperatures are temperatures corresponding to the curves given in Mr. Stead's paper. But it is a fact—the correction was actually made by Mr. Stead himself—that the true temperature is 100 degrees higher than that stated. This does not really affect the results obtained in the

paper mentioned, because the temperature is only used as a common abscissa to all the different curves which it gives. The present author has said a great deal about the design of valve sets and of valves without giving any definite figures on the subject of life; these would constitute a very valuable addition to the paper. Again, I wish to join issue with Prof. Fortescue on the rating of the valves. It is essential that there should be not only a dissipation rating of the valves but also an approximate input rating. Cases have arisen where it has been possible to exhaust a valve for a dissipation rating which would not actually be achieved by the user without either sacrificing a great deal in efficiency or raising his supply voltage above a convenient value. I am of opinion that the design of the electrodes with a view to the input rating is important. As regards the limit of voltage which a valve will withstand, I do not think that sufficient stress has been laid on the phenomenon of the extraction of electrons from a cold metal surface by a sufficiently strong electric field. This is a point to which designers of valves will have to give more and more attention.

Dr. W. H. Eccles: The paper contains, among much other matter, a larger collection of useful suggestions for design than any paper I can remember on the subject. It also contains many novelties; for example the author has arrived at the conclusion that the more economical way of working generating plant is to use the unsaturated part of the current curve. Four or five years ago the use of the saturation part of the characteristic curve was thought to be necessary for economy. On the whole I think that the author's work represents what might be called empiricism at its best. It is a mode of attack which I should like always to be able to follow and which I shall always recommend to every engineer. May I add that we all feel that the Admiralty is fully justified, judging by the papers we have had from the Signal School, in its policy of keeping up a large development department. The publication of the fruits of their labours is, we think, also justified and marks a departure from the Admiralty's pre-war policy, a departure which we should do well to approve.

Major A. G. Lee: In Fig. 28 the author gives the effects of changes of aerial tuning. Mr. Hansford has pointed out that when one obtains constant frequency by means of a separately excited grid one pays the penalty in a change of aerial current. This change of aerial current leads one into difficulties with the current or voltage limitations of the valves, unless one can ensure that the aerial constants shall not change beyond certain limits. We have found as a result of measurements of two different types of aerials—the flat-top Marconi aerial and another with a cage or "sausage" lead-up—that the "sausage" type varies in resonant frequency more than the other. It may, however, be improved upon very considerably. Another point of great interest in the paper is the methods of harmonic stopping. Mr. Hansford has already exhibited the diagram showing the method employed by the Post Office. Our general experience is that that circuit very efficiently eliminates the harmonics. If one does employ a condenser coupling in order to get a reduction in harmonics between the primary and secondary circuits one has to be careful that those circuits have no other form of coupling, because harmonics can get across from primary to secondary by stray couplings to quite a large extent. Another point of interest in connection with the measurements in Fig. 33 is how far from the station these measurements were made, because there is a possibility that harmonics can be radiated by the primary circuit as well as by the secondary. They do not travel very far from the primary circuit, of course, and probably these measurements were made fairly close to the station. Another kind of disturbance from valve sets is what is known as "key-clicks," which constitute a serious source of disturbance by a powerful valve transmitter. They spread from 100 to 200 m around the fundamental wave-length, and this means that it is quite impossible to locate another nearby receiving station within these limits of wave-length. This defect is probably also common to alternator stations. The marking and spacing method of signalling which maintains nearly constant amplitude on both frequencies, however, is not responsible for this particular defect; but the method is not liked in the Navy because of the necessity of listening-through. The details given in Table 2 are of great interest. Efforts are being made to increase the power of transmitting valves, and it is very satisfactory to know that the Navy has a valve with an output of 21 kW. The final choice of valve—silica, metal or glass—will depend on two factors: (1) the largest single unit that can be produced in either of the types, and (2) the economics of the case. Probably the second consideration will decide which type will survive.

Mr. H. Faulkner: The author states that the maximum value of anode filament valve P.D. with anode positive largely determines the efficiency of rectification. It seems rather strange, therefore, that in the example of design an arbitrary value should be taken for this voltage rather than attempting to reduce its value to the minimum possible. Later in the paper the author discusses the possibility of resonance of the circuit comprising the anode condenser high-frequency choke, etc., in the case of an I.C.W. transmitter. It is thought that, even without any conditions of resonance, in the absence of the smoothing condenser which normally provides the necessary bypass across the supply circuit the circuit would be a very dangerous one unless a suitable condenser were provided at some convenient position in the circuit or, alternatively, the inductance of the high-frequency choke were made large in comparison with the inductance of the secondary winding of the transformer. With regard to the stranded-wire tuning coils mentioned in the paper, I should be interested to know what acceptance tests are applied to the stranded-wire cable. My experience is that the normal commercial article leaves much to be desired with regard to insulation between the strands, and it is necessary to impose severe tests from this point of view. Imperfect stranding has a very bad effect on the high-frequency resistance of coils for radio frequencies, as Mr. Shaughnessy pointed out in his recent address * as Chairman of this Section. The author claims that the arrangement of valves in series results in increased efficiency of working over that obtained by using valves in parallel at, say, half

* *Journal I.E.E.*, 1925, vol. 63, p. 60.

the anode voltage. I cannot agree in principle: as in the case of rectifying valves, the principal factor governing the efficiency is the space-charge voltage necessary to give maximum anode current. In the case of valves connected in series it is clear that the permissible total anode voltage is increased, but at the same time the space-charge voltage is increased in proportion and it is difficult to see what is the advantage. It seems to me that the phase relationship between anode current and anode voltage can be adjusted by an adjustment of the proportions of the blocking condenser and the high-frequency choke. The Post Office experience as regards economy of change-over from spark to valve is similar to that of the Admiralty. At the conversion of the Stonehaven station practically every component of the spark set was utilized, with the exception, of course, of the disc dischargers and, I think, the "jigger," and the only additions required were the valves themselves and a few small auxiliary items.

Major H. P. T. Lefroy: When considering the design of radio transmitting apparatus, it is well to keep in mind the fact that a station only transmits in order that it may be received; hence transmission efficiency can only be considered in connection with reception efficiency. The latter is usually defined by a ratio, namely (strength of desired signals)/(strength of undesired signals), and factors that decrease the denominator of this ratio are as important for true efficiency as are those that increase its numerator. It is clear that improvement in the power efficiency of the transmitter will tend to increase the above numerator; but such improvement may tend also to increase the strength of the harmonics radiated, and such harmonics are undesired signals to stations with which the transmitter is not communicating, and thus tend to reduce the efficiency of radio communication as a whole. For radiotelegraphic reception, signal tone-filtering devices are very effective in reducing the above denominator; they normally exclude all but a narrow band of acoustic frequencies, so that, if the wave-length of the transmitter varies, the heterodyne note of the desired signals in the receiver may vary beyond the limits of this band and may thus be more or less filtered out, thus reducing the above numerator; such reduction will also occur, when using such a filter, if the ripple note of the high-tension supply to the transmitter modulates the received signals perceptibly. From the above, it follows that the true efficiency of any radiotelegraphic transmitting apparatus can only be ensured when the following four conditions are fulfilled: (1) Power efficiency; (2) constancy of wave-length; (3) purity of tone; and (4) absence of radiated harmonics.

Mr. G. Shearing (*in reply*): With reference to the remarks of Prof. Fortescue, I have deduced equations for the rectifier losses for a given voltage ripple based directly on the 3/2-power law, but I did not find them so easy to manipulate as those based on the assumptions given in the paper.

With regard to the grid circuit protection, the adoption of the resistance is solely to protect the grid circuit. Excessive grid currents which may cause breakdown of this circuit can be obtained for incorrect adjustment of the grid circuit when the anode current is below the safe value. This is illustrated in the curves of Fig. 19, in which the maximum value of the grid oscillatory current, for the case of no resistance, is of the order of 700 per cent of the value for correct condenser adjustment, and is dangerous for the grid circuit which is designed for small space requirements, whereas the corresponding value of the anode current of 0·5 ampere was perfectly safe for the valve itself. Again, the maximum anode current shown, of the order of 0·7 ampere, was a safe value. Resistances of this type, comprising a carbon lamp shunted by a resistance, the total value being of the order of 100 ohms, were applied during 1919–20 to the earlier transmitters and resulted in a reduction of breakdown of the grid coupling coils. An overload relay of the type shown in Fig. 24 and described on page 323 is fitted usually to protect the valves against excessive anode current; it is particularly to be noted that the anode, grid and aerial currents are practically the same for correct grid circuit adjustment for each value of the resistance.

FIG. C.—Anode current wave-form. Mean value = 0·52 ampere; d.c. supply power = 4·36 kW.

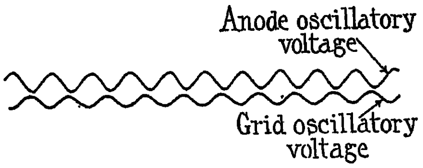

FIG. D.

Anode voltage = 4 250 (R.M.S.).
Grid voltage = 2 750 (R.M.S.).
D.C. supply voltage = 8 400.
Minimum anode-filament voltage = 2 230.
f = 400.

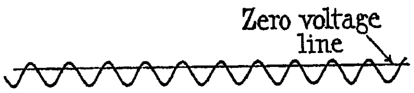

FIG. E.—Grid oscillatory voltage = 2 750 (R.M.S.).

The multiphase circuit of Fig. 16 can be made to give excellent results as regards ripple, comparable with that for two-wave rectifying units, provided that care is taken to ensure that each valve carries the same current in turn. With this circuit each valve filament has to be capable of supplying the total electron current for the case of a sine wave-form of supply voltage.

Whilst I agree that the method given of calculating the performance of the valve for an oscillatory circuit from the curves of Fig. 36 is only approximate, it is based on experimental observations, and the oscillograms of Figs. C, D and E taken for a type NT23 valve on a low-frequency oscillatory circuit show that the valve current wave in this case approximates to a flat-top form. At the same time it is true, as pointed out by Mr. Gossling, that the allowance of 50 per cent greater emission does cover the case of a peaky wave-form, but

our aim has been to avoid such wave-forms with a view to the reduction of harmonics, and the rectangular wave-form is a fair average assumption.

As regards circuit tuning, instructions based on laboratory measurements obtained for circuit adjustments on typical aerial systems are given to the operators.

For modern high-power valves with molybdenum or with water-cooled anodes, the maximum possible value for the oscillatory anode power dissipation is almost invariably less than the maximum permissible static power anode dissipation, due to the limitations imposed by valve geometry, inter-electrode voltages, and possibly filament emission as outlined on page 326. For this reason I prefer to assign first importance to the valve geometry. If the valve-operating voltage can be raised with safety to values greater than those at present employed, then it may prove possible for the valve oscillatory and static safe anode dissipations to approach more closely to each other. Improvement in this direction may be obtained by finally exhausting these valves under the oscillatory voltage conditions of practical use, and I am very interested in the remark of Mr. Gossling concerning the phenomenon of the extraction of electrons from a cold metal surface under a strong magnetic field.

Our experience so far has been that the filament life for transmitting valves is less than for rectifying valves. In our development work of the high-power valve since 1919 we had no earlier experience to draw on, and the tendency has been for us to increase the filament power and dimensions corresponding to lower temperatures since the first experimental designs. The filament life for transmitting valve types NT23 and NT24 varies from 400 to 1 000 working hours, whereas corresponding values for the NU21 and NU22 valves are 1 000 to 1 500 hours. The temperatures stated in the paper correspond to those given in Mr. Stead's paper, and the values he gives have been used consistently since 1919–20 for ready comparison in our experimental work.

As regards the reason for the adoption of the value of 3 000 volts for the maximum anode filament P.D., this depends on a number of conditions, and it is not necessarily practicable to reduce the value to the minimum possible considering the valve only, as suggested by Mr. Faulkner.

The main conditions may be briefly summarized as follows :—

(1) The minimum time during which it is desirable for the current-pulses to flow from each half of the transformer winding, since reduction of this time corresponds to increase of electrical and mechanical stress on the transformer and alternator windings and to an increase of harmonics in the secondary terminal voltage.
(2) The maximum amount of filament power it is desired to employ for the valve filaments.
(3) The minimum practicable diameter of the anode, relative to the filament for the voltage the valve has to withstand as an insulator.

As regards the design indicated in the paper it may be noted that for the rectified voltage of 10 000 the maximum instantaneous transformer kVA is $5 \cdot 46 \times 13\,000$, or 70, whereas the mean power output of the transformer is of the order of 18 kVA; this ratio must either not be excessive or, alternatively, it must be carefully specified to the makers of the transformer and the alternator plant for design purposes.

In reply to Mr. Grinstead, to operate the valve above the saturation bend corresponds to an increase of voltage across the valve for a given rectified power with reduced efficiency and increased valve heating, and the valve can be operated in this manner, at reduced power output, up to the permissible anode dissipation, by reducing the filament supply power. As regards the design of the grid, the value of m upon which grid closeness depends can be varied over a very wide range without affecting the performance of the valve when used on oscillatory circuits employing a considerable grid negative potential. Considerable variation of the valve design as regards electrodes, whether transmitting or rectifying, can be made subject to the valve being able to pass the required electron current at the specified voltage conditions. This is referred to (as regards the rectifying valve) on page 314.

It is not possible to differentiate between experimental and standard practice of the Admiralty, as the requirements are very exacting and diverse and one is usually not able to adopt the most straightforward technical design. The separate grid excitation circuit has great advantages for land-station working where fixed wave-lengths are the rule and aerial-swing can be reduced to a minimum; but for Naval use, where the aerial swing is greater and insulation more exposed to heavy sprays and seas, the change of aerial effective capacity with wet insulation may seriously prevent the aerial oscillatory current from building up unless an intermediate coupled circuit, separately excited, is employed. The circuit is but slightly better than the retroactive circuit for restarting under wet conditions, as stated on page 322. The size of the separate exciter valve has usually been of the order of one-sixth to one-eighth the size of the main valve. The statement on page 323 concerning the change of aerial current should have read "reduction of aerial current by 30 per cent of its best value" and this correction has been made for the *Journal*.

As regards the use of harmonic stoppers, these are being fitted to certain land stations, and in this connection, comparing the circuits of Figs. 32 and 34, the circuit diagrammatically shown in Fig. 32 has given the better results in practice. With the circuit of Fig. 34 it is necessary to ensure that both valves are balanced as regards their respective anode currents. I agree with Mr. Hansford that the description of Figs. 32 and 34 is brief, as I deliberately cut out further description in preparing the paper, to reduce its length. Our experiments so far made with capacity-coupled circuits have not been so satisfactory as those of the Post Office, but I presume the Post Office tests were on much longer wave-lengths than ours. I hope that comparative results for harmonic reduction, of the circuits referred to by Major Lee and by Mr. Hansford, will be published later. For the case of sets to be

operated on wide ranges of wave-lengths of the order of 600 to 6 000 metres we have experienced the difficulty referred to by Major Lee of subsidiary oscillations being generated by the various possible combinations of capacity and inductance with the main aerial circuit. Further, the overall efficiency has usually been reduced as the fine adjustments necessary for good efficiency on the wave-length range are prohibitive on account of space limitations. Incidentally, I should like to point out that the harmonic stopper described in Fig. 31 of the paper has the advantage of the capacitative anode tapping described by Mr. Hansford, since the harmonics have a path via the harmonic stopper condenser C_R, Fig. 31, which may be n^2 times as good as the path via the anode tapping inductance.

As regards the harmonic measurements in Fig. 33, these were obtained from readings taken with the key pressed immediately adjacent to the transmitting source, and the results obtained were in fairly close agreement with comparative signal measurements made by receiving in a ship at varying distances up to about 400 miles from the transmitter. The disturbance described by Major Lee, known as "key clicks," has been observed by us in experimental comparison of high-power valve transmitters at Horsea arranged for listening-through with an arc transmitter employing marking and spacing wave; the effect appears to be much greater for a given aerial current when employing high-tension signalling keys in the secondary than when signalling on the primary side of the high-tension transformer (which of course may not be practicable for high powers).

The series arrangements of valves were got out for higher supply voltages than were practicable for a single valve. The normal operating voltage for single valves requiring an input power of the order of 10 kW is increasing up to 14 000–15 000 volts, but we have operated valves in series at rectified voltages of the order of 20 000 volts and the arrangement is certainly very stable in action, as pointed out in the paper. Also, the circuit described in Fig. 24 enables either row of valves to be brought immediately into use by operation of the switches when the set is not required to be operated at full power; again this may be done if for any reason a single valve fails. No difficulty has been experienced in the design and manufacture of suitable filament transformers insulated between windings for high-frequency voltages of 10 000 to 20 000.

My remark *re* excessive complexity of valve connections had no reference to the comparison of series and parallel arrangement of valves; it applied to the advantage of the adoption of a larger valve unit over a number of smaller valves in parallel, and I am correcting the context to make this clear. Again, I think it should be clearly understood that the normal advantage of series operation is for the case when the supply voltage is greater than that which can be applied with safety to a single valve. It is undoubtedly true that for the smaller quantity of electricity required for a given power through the rectifying valves at the higher rectified voltage corresponding to valves in series, there is a gain of rectifier efficiency, as shown by the curves of Fig. 3. A gain of transmitting efficiency is also observed when employing two transmitting valves in series at voltages of the order of 50 per cent greater than the safe operation voltage for two valves in parallel. With reference to the use of a by-pass condenser for the I.C.W. transmissions, the smaller power sets developed up to 1918 were used mainly on relatively short I.C.W. wave-lengths and no transformer breakdowns occurred, as the stray capacity of the transformer windings was sufficient to carry the very small high-frequency current under the non-resonating conditions without excessive potential difference when an anode choke of the order of 20 000 to 30 000 μH was employed. I am doubtful whether much of the transformer inductance enters into the problem owing to the relatively small high-frequency impedance of the transformer winding stray capacity. Extension to longer I.C.W. wave-lengths during 1918 was found to give rise to the resonating difficulty referred to on page 317, and the small condenser was a simple solution now adopted for all sets.

The difficulty described by Mr. Faulkner with regard to the insulation between strands has not been experienced to the same extent by us; the enamelling of the wire is carried out to a specification imposing very severe tests. It is probable, however, that excessive heating of the wire may be due to the mutual inductance of the stranded wires not being the same for each individual wire per coil turn. The following procedure is desirable in stranding the cable. The wires should be built into groups of three wires and each group of the three wires should be twisted right-hand. Then three of these groups should be twisted left-hand to form larger groupings. These larger groupings should then be twisted three right-hand, and so on. This tends to ensure constancy of mutual inductance for each individual wire. Further, it is desirable not to impregnate the strands of the wire apart from the cable covering.

I agree fully with Dr. Eccles as to the importance of the unsaturated part of the current curve of the valve for power generation.

It is usually possible to adhere to the requirements laid down by Major Lefroy for the design of a land station, but for ship transmitters the additional practical conditions to be fulfilled may render the satisfaction of these requirements either much more difficult or not entirely possible.

INSTITUTION NOTES.

Associate Membership Examination.

The Council have decided to accept in lieu of Part I of the Examination the Higher Grade National Certificate or Diploma in Electrical Engineering, provided that the candidate satisfies the Institution in the subject of "English Essay."

Associate Membership Examination Results: October, 1924.

SUPPLEMENTARY LIST.*

Passed.

Barrs, H. H. (New Zealand).
Dalton, G. A. (South Africa).
Harvey, A. F. S. (Buenos Aires).
Prickett, J. H. (South Africa).

Passed Part II only.

Loveday, G. K. (South Africa).

Heat Engine Trials.

The Heat Engine Trials Committee of the Institution of Civil Engineers will present for discussion at a meeting to be held at Great George-street, Westminster, on Wednesday, the 25th March, 1925, at 6 p.m., the standard form or code for tabulating the results of a steam generating-plant trial. All interested in the subject are invited to attend and to take part in the discussion. Mr. W. H. Patchell, Chairman of the Panel responsible for drafting the code, will introduce the subject and will refer in particular to certain questions which it appears desirable to debate. Among these will be included questions relating to the make-up of the heat-account table, and to certain proposals in connection with recording the analysis of oil fuels. Discussion on other items in the code will also be welcomed. Copies of Mr. Patchell's introductory notes and of the code itself can be obtained on application to the Secretary of the Institution of Civil Engineers, Great George-street, Westminster, S.W. 1.

Briefly it may be stated that the code contains the description of the steam generating plant and the conduct and the results of trial or trials tabulated as follows :—

I. General information and design data.
   Specified performance.
   General description: (*a*) Furnace (solid and pulverized fuels, oil and gas fuels and waste heat); (*b*) boiler; (*c*) superheater; (*d*) economizer; (*e*) steam reheater; (*f*) air heater; (*g*) draught plant.
II. Methods of measurement.
III. Mean observations derived from log sheets and preliminary deductions.
IV. Final deductions and heat accounts.
V. Energy received for auxiliaries from outside sources.
VI. Net overall efficiency.

* See page 153.

Informal Meetings.

The following Informal Meetings have been held :—

57TH INFORMAL MEETING (27TH OCTOBER, 1924).

Chairman: Mr. W. B. Woodhouse (President).

Subject of Discussion: "The Interconnection of Power Stations" (introduced by Mr. W. B. Woodhouse).

Speakers: Messrs. H. M. Sayers, A. F. Harmer, W. E. Rogers, A. Williams, J. H. Sandiford, A. G. Hilling, J. F. Shipley, J. W. Robertson, W. F. Andrews, N. Brooksbank, A. W. Berry, J. R. Bedford, R. D. Gifford, D.Sc., V. N. Halliday, T. R. Renfree, R. V. Hook and A. J. Watts.

58TH INFORMAL MEETING (10TH NOVEMBER, 1924).

Chairman: Mr. A. H. Allen.

Subject of Discussion: "Research in the Cable Industry" (introduced by Mr. P. Dunsheath, O.B.E., M.A., B.Sc.).

Speakers: Messrs. G. L. Addenbrooke, P. Rosling, H. C. Silver, W. Day, J. H. C. Brooking, T. N. Riley, A. Collins, A. Rosen, E. S. Ritter, R. D. Gifford, D.Sc., W. G. Newberry, A. G. Hilling, H. Savage, J. Coxon and A. H. Allen.

59TH INFORMAL MEETING (24TH NOVEMBER, 1924).

Chairman: Mr. J. W. Beauchamp.

Subject of Discussion: "The Electrostatic Wattmeter used for Measuring Dielectric Losses in Cables" [introduced by Mr. N. A. Allen, B.Sc.(Eng.)].

Speakers: Mr. G. L. Addenbrooke, Prof. J. T. Macgregor-Morris, Messrs. A. Collins, A. Rosen, A. J. Tracey, R. M. Longman and J. W. Beauchamp.

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 January–25 February, 1925 :—

	£	s.	d.
Adkins, H. (Coventry)		2	6*
Aitken, W. (London)	1	1	0
Aldridge, D. W. (Prescot)		5	0
Allan, J. T. (Birmingham)		3	6
Anderson, J. (Glasgow)		10	6
Anderson, W. Y. (Birmingham)		5	0*
Andrews, E. (Barnsley)		10	0
Andrews, R. (S. Shields)		3	6
Andrews, W. F. (London)		10	0
Armstrong, R. E. (Leamington Spa)		5	0
Arthur, J. W. (Reading)		10	0
Atkinson, Ll. B. (London)	1	1	0*
Babb, H. C. (Musselburgh)		10	0
Baldwin, L. L. (Ahmedabad, India)		8	6
Baldwin, S. J. W. (Ahmedabad, India)		8	6

	£	s.	d.
Baldwin, W. L. (Glasgow)		10	0
Bamford, P. E. (Birmingham)		10	0
Barrow, L. L. (Sale)		5	0
Basil, D. A. (Stafford)		3	6
Baxter, W. (Hollinwood)		5	0
Beales, M. (London)	1	1	0
Bennett, H. J. (Southsea)		10	6
Birkby, H. (London)		10	0
Blanden, F. (Grimsby)		5	0
Boddington, F. S. (Southport)		5	0*
Bogie, A. (Edinburgh)		2	6
Bolton, F. (London)	1	0	0
Bose, S. N. (New York)		5	0
Brazier, C. J. H. (Castle Eden, Durham)		5	0
Brewer, A. E. (Evesham)		5	0*
Briggs, R. A. (Derby)		7	6*
Brough, L. G. (Wallsend-on-Tyne)		4	0
Brown, W. (Morecambe)		2	6
Browne, A. W. (Manchester)		10	0
Bull, M. J. (London)		5	0
Bullman, H. C. (Aberdeen)		10	0
Bulow, V. A. M. (Sheffield)		5	0*
Bunn, N. K. (Rainhill)		15	0
Burgess, A. B. (Glasgow)		2	6
Bush, V. F. (Redditch)		5	0*
Butcher, P. H. C. (Sutton Coldfield)		5	0*
Calverley, J. E. (Preston)		15	0
Carter, H. E. D. (Birmingham)		5	0
Carter, W. J. (Loughborough)		5	0
Cash, H. J. (London)		10	0
Castello-Sosa, A. (Mexico)		5	0
Chadwick, F. D. (Cawnpore)		8	6
Chalmers, J. W. P. (London)		10	0
Chatterjee, S. K. (Khandwa, India)		5	0
Chaytor, A. R. (Chesterfield)		12	6
Chisholm, G. G. (Glasgow)		5	0
Chubb, W. L. (Stoke-on-Trent)		5	0
Clark, J. E. (London)		5	0
Clarke, H. (Hayes, Middlesex)		5	0*
Collins, A. (Chingford)		5	0
Colquhoun, J. B. (Glasgow)		5	0
Comino, D. J. (London)		5	0
Conway, J. (Dundee)		5	0
Cooper, A. (Burton-on-Trent)		8	6
Cooper, C. V. (Aldershot)		10	6
Coward, A. C. (Swansea)	1	1	0
Cox, P. H. (Cheltenham)		8	6
Cozens-Cooke, W. (London)		5	0
Crawford, C. G. (London)		6	6
Cribb, E. H. (Coventry)		2	6*
Crompton, C. (Blackheath)		10	0
Cropley, C. P. (Burgess Hill)		10	0
Dallas, J. D. (London)	10	0	0
Dancer, W. (Birmingham)		5	0
Davids, W. da F. B. (Brazil)	2	0	0
Davies, P. G. (London)		16	0
Davies, W. (Chirk)		3	6
De Alwis, D. R. C. (London)		10	6
Debley, W. J. F. (Llantwit Vardre, Glam.)		5	0
Dickinson, D. W. L. (London)		10	6
Dorrell, H. B. (Bury)	1	0	0

* Annual Subscription.

	£	s.	d.
Driscoll, L. F. A. (Newport, Mon.)		4	6
Drucquer, L. (London)		5	0
Duke, G. E. (Walsall)		2	6*
Duncan, R. A. S. (Aldershot)		10	0
Eastwood, A. (Newcastle-on-Tyne)		5	0
Edwards, F. S. (Hale, Cheshire)		5	0
Edwards, W. G. (London)		5	0
Edwards, W. J. (Birmingham)		2	6
Elton, E. (Rugby)		2	6
Evans, E. W. (Swansea)		5	0
Evershed, S. (London)	2	2	0*
Eves, W. J. (Birmingham)		2	6
Fippard, A. J. (London)	1	1	0
Flanagan, J. (Middlesbrough)		5	0
Francis, L. B. (Birmingham)		2	6
Fuller, L. O. (Delhi)		5	0
Gallizia, E. (Birmingham)		3	6
Geary, F. A. (London)		5	0
Geipel, K. S. (London)	1	0	0
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THREE-WIRE DIRECT-CURRENT DISTRIBUTION NETWORKS: SOME COMPARISONS IN COSTS AND OPERATION.*

By HERBERT WILLOTT TAYLOR, Associate Member.

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SUMMARY.

This paper discusses the application of the following types of cables and methods of laying to the various parts of a three-wire d.c. network.

Types of cables: Single-core, three-core, and triple-concentric.

Methods of laying: Conduit, direct, and solid.

It endeavours to show that, wherever it can be adopted, the most satisfactory network is that composed of single-core lead-covered cables, the feeders being drawn into conduits and the distributors and services laid direct.

The paper also describes the "looped-neutral" service, the object of which is to facilitate the location of faults on the smaller sizes of triple-concentric vulcanized-bitumen distributors, and to improve the continuity of supply under fault conditions.

(1) INTRODUCTION.

Permissible current loading.—Before proceeding to compare the various types of systems, it is necessary to form some idea of the relative carrying capacities of cables laid under different conditions. No useful purpose would be served by comparing the costs of, say, a 0·5 sq. in. × 0·25 sq. in. × 0·5 sq. in. feeder made up of single-core cables laid direct in the ground, with that of a solid-laid triple-concentric feeder of the same cross-sectional area. For this reason it is necessary to find the sizes of the various cables which will give approximately the same performance for any given method of laying.

There are so many modifying influences that affect the safe current-carrying capacity of a cable, such as the type of ground in which it is laid, the depth and manner of laying, the nature of the loads and the construction of the cable itself, that it is impossible to fix any definite values unless all the prevailing local conditions are known. Some of these points are enumerated below:—

The method of laying the cable has a modifying influence. Where a single-core cable is laid direct in the ground the problem is a fairly easy one. When one comes to consider multicore cables and, perhaps, the bunching of cables, it is more difficult to estimate the temperature-rise for any given current.

With cables laid solid the chief factor that prevents any trustworthy figures being given is the nature of the material used for filling in the troughing. In some cases the thermal resistivity of this material is nearly as high as that of the cable dielectric, while in others it is considerably lower, almost equalling the value for damp earth. Until the question of the filling material has been more fully investigated, no loading tables will be available. For purposes of comparison, however, it has been assumed that for a vulcanized-bitumen cable laid solid the maximum permissible loading will be considerably lower than for an armoured cable laid direct, and about the same as for a lead-covered cable drawn into a duct.

The chief variable quantity that renders a comparison difficult when considering drawn-in cables is the layer of air that surrounds a cable in a duct. It is this thin layer of air that offers the greatest resistance to the flow of heat emitted from the cable and, as it may or may not be in motion, its lagging effect is very problematical.

Again, the carrying capacity of a cable depends upon its heat emissivity, which is inherently bound up with its design. It is obvious that a single-core cable completely surrounded by earth at a uniform temperature will be able to dissipate the most heat.

In a triple-concentric cable neither of the two inner cores borders directly upon the surrounding soil. This means that all the heat generated in the inner core has to pass through both of the other cores before it leaves the cable. It will readily be realized from this fact that for a given current in all cores the inner core will be by far the hottest, and hotter than any core in a three-core cable of the same sectional area and carrying the same current. Although the outer core, having a very good cooling surface, will operate at a much lower temperature, no advantage can be taken of this, as the safe current density that can be applied is limited by the temperature of the hottest core, which means that a triple-concentric cable will have a lower rating than either a single-core or a three-core cable.

Much very useful information on this subject is contained in the Second Report on the Research of the Heating of Buried Cables, issued by the British Electrical and Allied Industries Research Association (see *Journal I.E.E.*, 1923, vol. 61, p. 517), and, from the information given in this Report, Table 1 has been compiled as representing average conditions. This table shows the maximum permissible currents that can be applied to single-core, three-core and triple-concentric cables as used on a three-wire d.c. network with the three methods of laying. It should be noted that on a three-wire system the neutral conductor carries little or no current, so that the ratings can be increased above the values that would apply if all cores were carrying the same current.

* This paper was originally submitted in the form of a thesis in lieu of the Associate Membership Examination.

(2) Feeders.

Type of Cable.

When a network is first laid down it is, as a rule, only possible to anticipate the districts at which the heaviest loads are likely to occur, the probable amount of load at each of these districts being too indefinite to warrant any variation in the size of the feeders. It is therefore usual to decide upon the number of nodal points that are necessary and to connect these to the station with feeders of equal size. From electrical considerations the more nodal points there are the more efficient will be the operation of the system, but economic facts have to be faced and a compromise reached. It is well to err on the side of fewer feeders at the beginning, because, when an undertaking is young and therefore struggling, any unnecessary capital outlay is to be avoided. Another fact that lends support to this precaution is that the natural and most economic nodal points for a town frequently move, owing to the erection of new buildings and the migration of people from one part of the town to another, this generally being from the centre outwards. New feeders can be laid when necessary, by which time the extra expense can better be borne and an indication given as to the most suitable place for a new nodal point to cope with any migration of load that is taking place.

The choice of the size of cable for a feeder is more an economic than an electrical problem. This is because the question of voltage-drop on such a cable is only of secondary importance, as there are no limiting factors imposed by the Electricity Commissioners as in the case of distributors. Any variation in the value of this drop can be counterbalanced by an equal variation of the busbar voltage, so maintaining a constant pressure at the nodal points. It is therefore confined to a consideration of the heating effect of the current and a compromise between the energy lost in the cable and the capital charges. The most economical size of cable is obtained when the cost of the energy wasted, plus the capital charges for the part of the plant necessary to supply this loss and for the cable itself, is a minimum. This is expressed in the following formula:—

$$\text{Total charge (in £)} = \frac{I^2 rTd}{1\cdot 2 \times 10^6} + \frac{I^2 r C_1 p_1}{0\cdot 5 \times 10^6} + C_2 p_2$$

where the symbols have the values given in the appendix.

This condition may be considered ideal as, in practice, other factors, such as anticipation of future load, compel larger cables to be laid down than may be determined by this formula for the immediate requirements. It is, however, a useful guide in deciding whether a system is working in the most economical manner, or whether there would be any financial advantage in laying an additional feeder.

Single-core cables.—From the point of view of operation it is undoubtedly the best policy to use single-core cables for feeders, as advantage can be taken of their high current-carrying capacity. It is for this reason that some undertakings have adopted such a system of feeders, even though the rest of the network is made up of three-core or triple-concentric cables.

The greatest advantage in the use of single-core cables is the small amount of inconvenience caused to consumers under fault conditions, this being particularly evident when followed up by a similar type of distribution system. This point is fully considered in the section dealing with distributors.

Three-core and triple-concentric cables.—Between the other two types of cables there is not much to choose, any advantage resting with the three-core cable, whose maximum current-carrying capacity is rather higher than that of the triple-concentric cable. Joints on three-core cables are also simpler, but this is not so important on feeders where there are comparatively few; on distributors, however, the fact assumes much greater importance. The use of three-core cables is limited

Table 1.*

Maximum Permissible Constant Current Loading.

Area of live conductors (neutral core half the size of outers)	Cables laid direct (lead-covered and armoured)			Cables drawn in (plain lead-covered) or Cables laid solid (vulcanized-bitumen)		
	3 single-core cables	3-core cable	Triple-concentric cable	3 single-core cables	3-core cable	Triple-concentric cable
sq. in.	amps.	amps.	amps.	amps.	amps.	amps.
0·1	298	263	249	202	185	162
0·15	367	331	313	261	238	208
0·2	438	390	371	317	290	254
0·25	497	447	421	373	338	295
0·3	559	501	478	428	388	340
0·4	665	589	562	526	474	415
0·5	748	669	641	604	545	482
0·6	845	—	724	696	—	552
0·75	949	—	812	800	—	634
1·0	1 158	—	997	1 012	—	800

* The values given are for sandy loam with 10 per cent moisture content, and clay with 20 per cent moisture content.

to sizes up to 0·5 sq. in., cable manufacturers being unwilling to guarantee larger sizes. This disadvantage is not shared by the triple-concentric cable.

Method of Laying.

Conduit.—In deciding the best method of laying feeders, the local conditions are always the governing factors, and these will not be similar in every case. The type of roadway met with in the centre of a town, in which area the bulk of the feeder system will generally be situated, is often of a very different nature from that in the outlying districts, and this fact might warrant additional initial expenditure with a view to future saving in the event of probable faults and possible extensions. For this reason it is often considered advisable to incur a little more trouble and expense in drawing the feeders into conduits in order to reap, at some future time, the advantages derived from such practice, amongst which are :—

(1) Rapid localization and repair of faults.
(2) Low cost of increasing the size of the feeder.
(3) Saving on capital charges due to the possibility of installing a cable sufficiently large to cope with loads of the immediate future, thus avoiding having buried in the ground a large quantity of idle copper which is not then required and from which no return will be forthcoming for many years.
(4) Less depreciation.

The first of these points, namely the rapid localization and repair of faults, is vitally important in a system whose feeders, during certain hours of the day, are loaded almost to their utmost capacity. The ease with which a faulty length of plain lead-covered feeder drawn into conduits can be located and replaced, as compared with the amount of time spent in taking up sets and breaking through a concrete roadway foundation to gain access to a direct- or solid-laid cable, perhaps in several places before the fault is located, may prove invaluable when the other feeders are in imminent danger of suffering permanent damage due to overloading. The question of the cost of repairs is more or less bound up with the speed with which they are carried out, as time undoubtedly means money, whether reckoned in wages or in loss of revenue.

The conduit system has the advantage that when feeders of too small a section may have been originally installed due either to errors in calculations or to the shifting of the more heavily-loaded districts, the mistake can be rectified at a minimum cost. Advantage can often be taken of this good quality of the conduit system by intentionally installing a smaller size of cable than will ultimately be required, but large enough for loads of the immediate future. It will readily be seen that if, say, a 0·25 sq. in. feeder will carry all the load that is likely to be required for 10 years, after which it might be advisable to install one of 0·5 sq. in. cross-section, there will be a considerable net saving in capital charges due to the fact that the extra cost of the 0·5 sq. in. feeder during those first 10 years when the major portion of the copper will be lying idle and bringing in no return, will not have to be met. Even this arrangement can be improved upon by drawing another feeder into spare ducts, laid at the same time as the others, the two cables then operating in parallel as one feeder. This obviates the loss that would be incurred by drawing out and scrapping the original feeder. The heavier initial cost occasioned by the increased number of ducts to be provided is only slight, particularly in the case of multicore cables. It is also conceivable that, due to the causes mentioned above, the size of the feeder might never require to be increased, the result being a permanent saving only rendered possible by letting the future take care of itself more or less.

The possible amount of depreciation is much less in the conduit system than in either of the others because, should the cable break down or require to be replaced due to obsolescence or other reasons, the only renewable part is the cable itself, whereas in the case of the direct- or solid-laid cable the whole cost of the mains is lost, all the original trench work and reinstatement of the roads has to be done again, and probably the protective material will have to be renewed. If the copper and lead of the recovered cable are sold, the only loss will be the insulation, the cost of manufacture and the labour of pulling in and jointing the cable.

There are a few points that must be carefully borne in mind when laying down a conduit line. The position of other existing pipes should be ascertained before the work commences, and trial holes have generally to be opened up along the proposed route to find a clear course. This information can often be obtained from the various authorities, but in old streets this is seldom the case, as a number of old pipes, particularly drains, will be discovered of which there are no records. The positions of these obstructions must be ascertained in order that the conduits may be laid so as to drain into the draw boxes and any dips or hollows in which water could collect and, by freezing, cause damage to the cable and conduits. Another reason for the avoidance of dips and twists in a conduit line is that, whilst it makes it more difficult for a cable to be drawn in, it renders it almost impossible to draw out a cable that has been allowed to settle and take up a definite shape for perhaps a number of years. Where there are no obstructions, a depth of 2 ft. to the top of the conduit is ample; but in the main thoroughfares of a large town a depth of from 3 to 4 ft. or even more is necessary to enable all obstructions to be avoided. Such roadways often appear to the electrical mains engineer to be a tangled mass of gas, water and drain pipes with sometimes Post Office cables, tramway feeders and hydraulic mains added to thwart his endeavours to obtain a straight conduit track. It is in such roadways that the direct-laid cable shows to particular advantage, as it can be run to avoid such obstructions.

If concrete is used as a protection for the conduits, with the intention of saving them from the crushing strain of very heavy traffic, it should be laid underneath and packed round the sides as well as on the top. If intended merely as a protection from picks, it need be placed only on the top and at the sides. In either case it should have a smooth finish to enable it to be recognized by any workman opening the ground later as being there for a purpose and not to be smashed up

as a casual obstruction. The concrete surrounding the conduits also preserves their alignment and renders them gas- and water-tight; thus minimizing the risk of explosion or electrolysis. In the opinion of the author, the use of concrete is unnecessary unless in exceptional circumstances.

Plain lead-covered cable and earthenware conduits should be used. Whilst braiding certainly protects the lead sheathing during drawing-in operations, and steel-wire armouring, in addition to this, takes the strain off the lead, these will rot away after a number of years in a wet duct and effectively jam the cable should any attempt be made to draw it out.

Cables laid direct.—A fact that becomes quickly apparent when considering the laying of a cable direct in the ground is the ease with which such work can be carried out. There is no need for the same amount of preliminary caution to be taken as for laying a conduit track along a main road. The fact that an obstruction is easily passed by this method is often a deciding factor in its favour.

The life of a lead-covered cable laid in good ground such as clay or sandy soil has not yet been determined, but the fact that such cables on being examined after 15 or 20 years' service show no signs of deterioration, would appear to indicate that their useful life is very considerable.

For feeder work full advantage can be taken of the high maximum permissible loading of the direct-laid cable. This might in some cases enable a smaller size of cable to be used than if it were to be laid solid or drawn into conduits.

Two factors have to be borne carefully in mind when laying cables direct, viz.

(1) Electrolytic action due to stray currents from other sources.
(2) The corrosive action of certain types of ground.

When the cable runs for a considerable distance parallel to a tramway track, a portion of the earth current may be induced to leave the track and return along the lead covering of the cable. This can be guarded against by laying the cable solid or drawing it into watertight conduits over that portion of the route on which electrolysis might be expected.

In ground largely composed of ash or slag there is a certain amount of free sulphur tetroxide which, when dissolved by any water that happens to penetrate through, forms a weak solution of sulphuric acid. This would rapidly corrode the armouring of a cable laid direct in such ground. The danger can be avoided by the methods mentioned above or by the importation of a quantity of clay, if such a supply is easily available, in which the cable is embedded and through which the acid cannot penetrate.

Cables laid solid.—The system commonly known as the "solid" system was introduced by Messrs. Callender's Cable and Construction Co., Ltd., and marked a great advance on the methods previously employed. Practically the only occasions on which this system is used to-day is when local chemical or electrolytic action would be probable on a cable laid direct. Even when such a course is adopted, plain lead-covered cable is preferable to the vulcanized-bitumen sheathed cable, for the following reasons:—

(1) The cost is lower.
(2) The continuity of the lead sheathing is maintained where the rest of the system, following modern practice, is composed of lead-covered cables.
(3) Similar cable may be used for drawing into conduits on other parts of the system, and so the amount of cable to be kept in stock is reduced.
(4) Freedom from damage to other adjacent roadway works in the case of a prolonged leakage to earth. This is particularly liable to occur on single-core vulcanized-bitumen cables laid solid.

This latter fact was recently very forcibly demonstrated to the author. Two substations were interconnected by three single vulcanized-bitumen cables laid solid in the same wooden troughing. The Post Office had trouble with one of their trunk feeders and, on drawing out the faulty length of cable, electrolysis was found to be the cause of the breakdown. Shortly afterwards another fault due to the same cause developed on a local feeder lying in a duct close to the trunk line. While this was being repaired a heavy fault on the supply undertaking's interconnector was reported, the heavy protective fuses at both stations having blown and about 4 ft. of the cables having burnt completely away at a place adjacent to where the trouble had occurred on the telephone cables. It was clearly a case of a slight fault being fed unnoticed for a considerable time, gradually increasing until it developed sufficiently to give some indication of its presence. Had lead-covered cables been used on this interconnector, and the lead securely bonded to earth at both stations, the fault would have immediately developed sufficiently to blow the station fuses and the supply undertaking would not have had to meet an account of over £250 for damage to Post Office cables.

Another point against the use of even single-core vulcanized-bitumen cables is that no advantage can be taken of the special arrangement—dealt with below under the heading "Distributors"—which enables the continuity of supply to be maintained in almost every breakdown, when single-core lead-covered cables are used throughout the system.

Modern practice is to use earthenware troughs because:—

(1) They are more easily laid down and better joints are possible between two troughs.
(2) They are unaffected by acids contained in the surrounding ground, resulting in long life.

It is well known that all wood contains certain vegetable acids, chiefly acetic acid. If a wooden trough is laid in damp ground it will quickly deteriorate and the acid will ultimately attack the cable. It is for this reason that wooden boxes should never be used for enclosing joints.

When laying the troughing, pockets should be carefully avoided because any water that manages to find its way into the troughing will accumulate at such places

and, in time, percolate through the bitumen and destroy the cable. To do this it sometimes means that a deeper trench has to be excavated than is the case when laying a cable direct, to enable the troughs to be laid underneath most of the other roadway obstructions. A depth of about 2 ft. 6 in. will generally be found sufficient for this purpose. The troughs should not be laid directly on a bed of clay when the ground above is of a porous nature, as surface water is liable to collect at such a level and perhaps find any weak spot in the troughing. In such cases it is better to deepen the trench slightly to allow the cable to be completely surrounded by clay. A foundation of some pervious substance such as loose stones or sand is beneficial, as water will quickly soak through and leave the cable comparatively dry, instead of remaining in the vicinity of the cable.

Before the bitumen is run in it is essential to see that the troughing is perfectly dry inside. Should any appreciable amount of moisture be allowed to remain, blow-holes will be formed in the bitumen, through which, in time, water will percolate to the cable. (This is a very trying feature of solid-laid cables.) The cable is then covered with hot bitumen which is allowed to set. The reason for having the first filling fairly hot is to make it sufficiently thin to ensure it filling up the small gap which is formed between the bottom of the cable and the trough, due to the cable resting on the saddles, and thus prevent the formation of any air spaces. It also serves the purpose of helping better to expel, before it sets, any moisture that might be left in the trough. The remainder of the trough can be filled up with bitumen at a temperature of about 250–300° F., and if the tiles are fixed before this sets they will be firmly held in position.

Pilot Cables.

As feeders are usually accompanied by pilot cables, the cost of these pilots might be considered in conjunction with those of the feeders themselves. The cost of installing a pilot with any particular type of feeder is not always the same, nor is the additional material to be provided similar in every case. This difference is, however, so small compared with the cost of the feeder itself that pilot cables have been omitted when arriving at the costs of the various types of feeders shown in Table 3.

Costs of Feeders.

From the figures given in Table 1 a set of curves, shown in Fig. 1, have been drawn from which the respective sizes of cables that have to be used for a given load and method of laying can at once be determined. For the purpose of comparing the cost of the different systems for feeders, the respective sizes necessary to cope with a maximum continuous load of 500 amperes are taken as being :—

It is not of course suggested that, where the size indicated in the above list is not a standard, a cable should be specially constructed to meet the specific requirements. As it is necessary, however, to have some definite basis of comparison, the costs of the sizes of feeders which would give the same results in practice are considered, and where these are not standard cables their costs have been calculated from those of the nearest standard sizes.

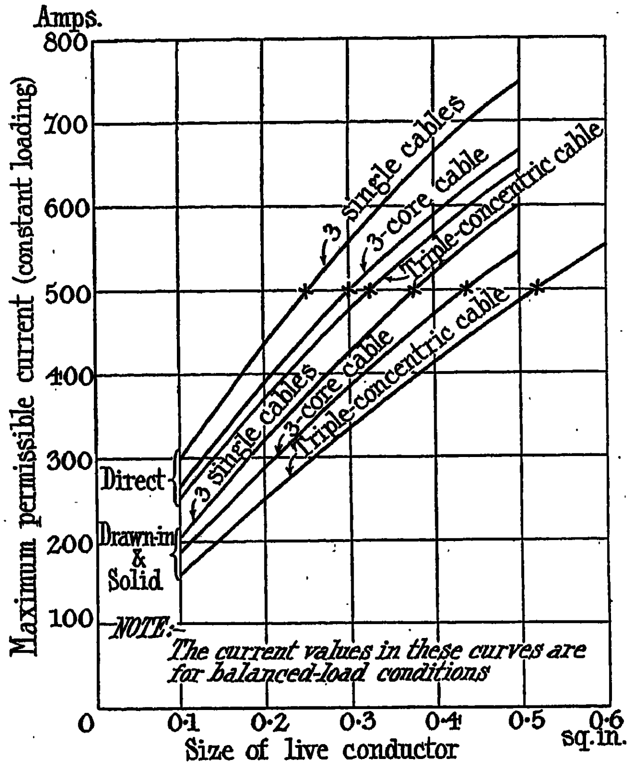

Fig. 1.

The costs of the various systems are shown for two types of roadway, namely :—

(1) Sets on a 6-in. concrete foundation.
(2) Waterbound macadam.

Table 2.

Depth of Track for Feeders.

Type of ground surface	Cables laid direct	Cables drawn in	Cables laid solid
	ft.	ft.	ft.
Sets + 6-in. concrete foundation . . .	2	4	3
Waterbound macadam	2	3	2

(1) 3 single-core cables (2) 3-core cable (3) Triple-concentric cable	Paper-insulated, lead-covered, steel-tape-armoured, laid direct	= 0·25 sq. in. × 0·125 sq. in. × 0·25 sq. in. = 0·3 sq. in. × 0·15 sq. in. × 0·3 sq. in. = 0·325 sq. in. × 0·1625 sq. in. × 0·325 sq. in.
(4) 3 single-core cables (5) 3-core cable (6) Triple-concentric cable	Plain lead-covered drawn-in and paper-insulated vulcanized-bitumen laid solid	= 0·375 sq. in. × 0·1875 sq. in. × 0·375 sq. in. = 0·44 sq. in. × 0·22 sq. in. × 0·44 sq. in. = 0·525 sq. in. × 0·2625 sq. in. × 0·525 sq. in.

The depth of track required for each of these types of roadway will not always be the same for all methods of laying. Table 2 shows the depths of tracks allowed for in estimating the results shown in Table 3.

The figures given in the latter table show that, wherever local conditions permit, three single-core feeders are the cheapest to lay down. When this fact is considered together with the technical advantages of this type of cable, there must be very exceptional reasons to cause any undertaking not hampered by restricted road space, to adopt a multicore cable for feeder work.

This table shows, exclusive of cable, the portion of the original expenditure that will have to be reincurred when it is necessary to increase the size of the feeder. It will also be seen that the harder the type of roadway, i.e. the more it costs to excavate and reinstate, the more substantial are the benefits derived from the conduit system.

(3) DISTRIBUTORS.

Single-core cables.—Owing to the ± 4 per cent voltage variation at consumers' terminals stipulated by the Electricity Commissioners, the choice of the type of cable to be used for distributors is very rarely affected by the maximum current-carrying capacity, the size required depending upon the voltage-drop when the cable will be carrying the maximum current with which it will have to cope.

TABLE 3.*

Cost of Feeders (500 amperes) per 100 yards.

Type of roadway	Lead-covered, steel-tape-armoured, laid direct			Plain lead-covered, drawn-in			Vulcanized-bitumen, laid solid		
	3 single-core cables	3-core cable	Triple-concentric cable	3 single-core cables	3-core cable	Triple-concentric cable	3 single-core cables	3-core cable	Triple-concentric cable
	£	£	£	£	£	£	£	£	£
Sets on a 6-in. concrete foundation	230	238	238	308	308	320	301	309	323
Waterbound macadam ..	146	153	153	218	218	230	212	220	233

It is also apparent from these figures that the cheapest way to lay cables is to lay them direct in the ground. There is little to choose between the conduit and solid systems, but both these are considerably more expensive to install than the direct system.

As already pointed out, the first cost in laying down a feeder is not the only consideration. When provision has to be made for future extensions and when the cost of repairing faults in cables laid under certain types of roadway that are both expensive to excavate and to reinstate is borne in mind, a considerable ultimate saving will be effected by incurring the increased initial cost of the conduit system, a fact clearly demonstrated by an examination of the figures shown in Table 4.

Apart from the cost of various types of distribution systems, the most important factor is that of continuity of supply in case of breakdown, and in this respect distributors composed of three single-core, lead-covered cables, used in conjunction with a similar type of feeder, form the best arrangement. This is because a fault can occur on one core without either of the others being affected, a rare occurrence on a multicore cable. Should one of the live cables break down, this cable alone need be cut out (provided that, by so doing, excessive load would not be thrown upon the neutral cable), the con-

TABLE 4.

Cost of Increasing the Size of Feeders per 100 yards (exclusive of cable).

Type of roadway	Lead-covered, steel-tape-armoured, laid direct			Plain lead-covered, drawn-in			Vulcanized-bitumen, laid solid		
	3 single-core cables	3-core cable	Triple-concentric cable	3 single-core cables	3-core cable	Triple-concentric cable	3 single-core cables	3-core cable	Triple-concentric cables
	£	£	£	£	£	£	£	£	£
Sets on a 6-in. concrete foundation	139	128	130	19	12	14	186	167	166
Waterbound macadam ..	54	44	46	19	12	14	96	77	76

* The costs shown in Tables 3 and 5 are based on the price of cables when the costs per ton of copper and lead were £60 12s. and £27 10s. respectively.

sumers connected to the other "side" being in no way affected.

A simple earthing device at the station reduces to a minimum the possibility of even this partial disconnection, and at the same time diminishes the cost of network boxes by allowing the more simple and reliable link box to be substituted for the majority of the fuse boxes (see Fig. 2). When an earth occurs on one of the "outers" it simply blows the light earthing fuse, and the neutral and other outer are respectively raised or lowered to 240 volts and 480 volts above or below

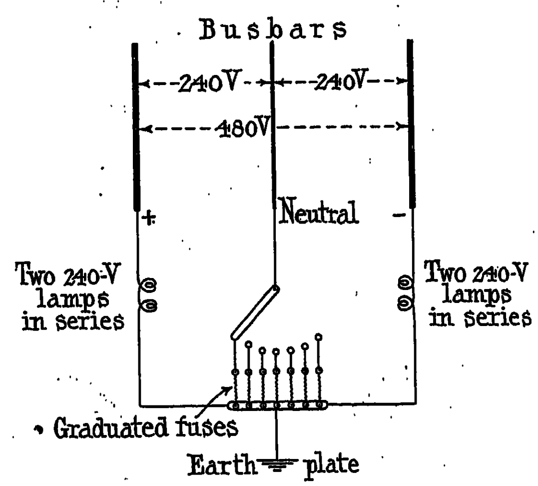

FIG. 2.—Method of earthing the neutral bar at the substation.

earth potential, as the case may be. The system will then continue to operate with one of the outers earthed instead of the neutral. Whilst this involves no danger to the electrical system, there is a greater risk of shock from the higher potential at which the unearthed pole is then operating. Such a fault must therefore be cleared as soon as possible.

system), in order to isolate completely the district in which the fault has occurred and allow the rest of the supply to continue undisturbed.

A point in connection with this system of earthing that should be carefully borne in mind is that the neutral cable under normal conditions may have an earth fault without the supply being in any way affected. Should an earth then occur on either the positive or negative cable there will be a short-circuit, varying in magnitude according to circumstances, between the two faults, and this will remain until one of the faults burns itself clear or is isolated by the operation of fuses. To guard against this possibility the neutral should, at periodical and convenient times, be raised to the potential of one of the outers through a light copper fuse, and any earth faults thus detected should then be immediately located and repaired.

Due to the fact that the potential is removed from the fault when the light earthing fuse at the station is blown, very little damage is usually done to the cable, provided that water has not penetrated through to the insulation. It is very often found in such instances that a new piece of cable is not necessary, as the fault can be repaired by simply stripping back a portion of the lead covering and, after taping the damaged part of the insulation, sealing it up in a cast-iron joint box or lead sleeve. This considerably reduces the cost of making the repair.

When the actual repair of a fault on one of the cables is considered this system shows up to further advantage, because:—

(1) The work can be left over, if desired, until such time when the least inconvenience will be caused to the consumers.

(2) When locating the fault, only the faulty side need be disconnected.

(3) The time taken to make a straight joint is very much less than with a multicore cable, and therefore the distributor can be put into commission again in a shorter time.

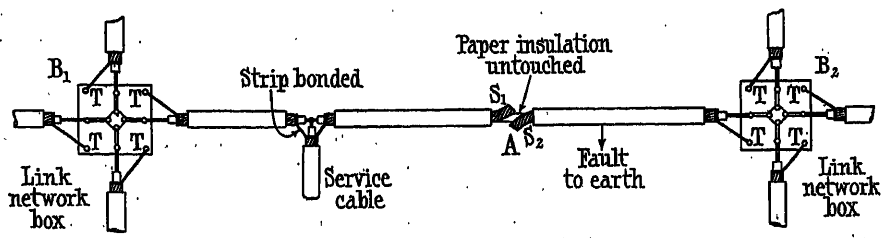

FIG. 3.—Testing-strip connections.

This arrangement offers no relief to the network when a fault takes place between cables, an occurrence which, though uncommon, must be provided for. For this reason it is not advisable to run the network without any fuses whatever, for should a short-circuit develop between two cables the fault must burn itself clear. During this time the cables leading up to the fault are liable to damage and the supply for the whole town is subjected to violent fluctuations of voltage. This difficulty is overcome by installing a few heavy fuse network boxes at certain points (their exact position being determined by the layout of the particular

By using a cable in which is incorporated a thin copper testing-strip, lightly insulated from the lead sheathing, it would be possible to locate a fault without actually cutting the core, which means that there would be no need to disconnect the faulty cable until the fault has been found and everything is ready for effecting the repair. In fact, if the cable is fed from both ends and it is found necessary to insert a new length of cable, this could often be done without interrupting the supply at all.

The method of connecting up this copper strip is shown diagrammatically in Fig. 3. It should be bonded across all straight joints and service joints on the cable

and brought to a terminal in each network box. Being lightly insulated from the lead covering, under normal circumstances it should test clear of earth and of the core. Its value in aiding fault-finding is based on the assumption that wherever a fault occurs from the core to earth the strip will be brought into contact with either the core or the lead covering, perhaps both. By testing to earth at the terminals T the faulty strip could be located; then by cutting this strip and testing both ways the fault may be found without interrupting the supply or cutting the cable, resulting in fewer straight joints.

A further advantage of the use of single-core cables is that the numerous tappings taken off distributors are more simple and easy to make and therefore more reliable. Also, when making such connections it is not necessary to make the cable dead. This fact, from the points of view both of the supply undertaking and the consumer, has beneficial results, because there is no loss of revenue during the time the connection is being made, and no inconvenience is caused to consumers.

This latter reason is of even more importance than the former and is often not fully appreciated by the officials of some undertakings. A comparatively trivial loss to the supply undertaking might be a matter of considerable concern, for instance, to small shopkeepers who use motors in their businesses. Interruptions should be cut down to a minimum as they only tend to cause dissatisfaction with electric supply. Many new consumers are obtained on the recommendation of old ones; their goodwill is therefore something to strive for and no effort should be considered too great, no detail too trivial, in the endeavour to establish it on a firm and lasting basis.

Three-core cables.—A network in which three-core cables are used for the distributors has not the same attractive features as those outlined in the system described above. The earthing of the neutral through a light fuse is unsuitable with such cables. The reason for this is that in a three-core cable, whilst it is possible to have a fault to earth on one live core without the others being affected, the time usually necessary for the trouble to spread and cause a short-circuit between cores is too brief for any material advantage to be gained by its adoption. It is thus usual for the neutral to have some form of permanent earth connection and for suitable protection to be provided to operate on a fault to earth or between cores.

The protection of a distribution system is necessarily a compromise between conflicting conditions. On account of their low cost and simplicity, fuses installed in network boxes or pillars at convenient junctions of distributors are relied upon to isolate a faulty section. The inherent weakness of the fuse is, however, plainly demonstrated on heavy faults, when, due to its lack of discrimination, large healthy areas are cut off together with the bad ones. For this reason, fusing points should not be multiplied unnecessarily. Besides being more expensive, the introduction of fuse boxes in the place of the link boxes decreases the reliability of the network.

As it is not necessary to cut any of the cores when a service connection is being made, the supply need not, in cases of urgent necessity, be interrupted during such time; but wherever possible it is better to make the distributor dead, as this allows the jointer to work in absolute safety and better workmanship is thereby obtained.

Trouble has recently been experienced on three-core distributors due to the straining of the cores when they are wedged apart to allow service connections to be made. When such connections are numerous, this strain may become serious. To overcome this difficulty, Messrs. Callender's Cable and Construction Co., Ltd., have produced a three-core cable the section of which is shown in Fig. 4. In the centre is a hemp core, around which are placed the three conductors which, in turn, are separated from one another by means of three more hemp cores. When a joint is being made these hemp cores are all cut away, thus leaving the conductors sufficiently spaced to allow the soldered connections to be effected without any straining whatever, and with much less risk should the cable be alive whilst the work is being done. Though a vulcanized-bitumen cable is shown in Fig. 4 the lead-sheathed type is more commonly used.

Triple-concentric cables.—The triple-concentric cable has such obvious disadvantages for low-tension d.c. distribution systems that it is remarkable that any

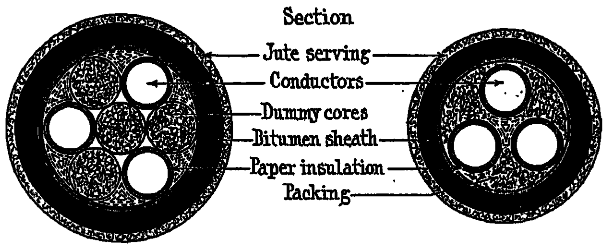

FIG. 4.—Three-core, paper-insulated, vulcanized-bitumen cable with dummy cores, and its diameter compared with that of a standard three-core cable.

undertaking ever adopted it for that part of a network where, owing to the smaller sizes of cables generally used, a three-core cable is possible. It has most of the disadvantages of the three-core cable enumerated above, as well as additional ones, against which it can only show a slight superiority in a reduction of cost and diameter. In addition, there are disadvantages arising out of the method of jointing. How the outer cores have to be stripped back to give access to the inner core is plainly shown in Fig. 6. To do this it is essential to make the cable dead if due consideration is to be given to the jointer's safety. Furthermore, when the connection is taken off the inner core, definite gaps are left in the continuity of the outer and middle cores and these have to be bridged by special fittings, resulting in two soldered connections on each of these cores. It will readily be appreciated that, however well these soldered connections are made, they can never be as reliable as the unbroken core of a three-core or single-core cable; moreover, joints have sometimes to be made under very adverse conditions which militate against good workmanship.

The inner and middle cores of a triple-concentric cable are usually connected to the positive and negative poles, the smaller outer core forming the neutral. This arrangement is maintained throughout the system so

that a joint cannot unwittingly be made with the wrong polarity.

With lead-covered armoured cables laid direct there would, however, seem to be something in favour of the outer core being made positive, the middle neutral, and the inner negative. In this case the lead sheathing, which is bonded throughout the network, provides a direct metallic connection between a faulty positive core and the station earth plate. Should a cable so connected be damaged, perhaps by the inadvertent blow of a pick, causing the lead sheathing to be pierced and come into contact with the live outer core, a fault is immediately apparent and can be repaired at once and at a low cost, which cost can be recovered from the authority responsible for the damage.

Supposing, however, that the outer core had formed the neutral, the man with the pick would not be aware of any trouble and no indication would be perceived at the station. After a lapse of perhaps months, when all recollections and evidences of the roadway having been disturbed have gone, a fault will be found to have developed due to water penetrating through the punctured sheathing. The fault is not now so easily traced and perhaps large expenditure is incurred which would not have been necessary had the circumstances been as in the case previously described. Moreover, due to lack of concrete evidence, blame cannot be fixed on any other authority, which means that the whole cost of the repair has to be borne by the supply undertaking. Making the outer core positive would also tend to prevent moisture from penetrating to the inner portions of the cable.

Method of Laying.

Drawing cables into ducts offers no considerable advantage for distribution work, so that the choice is limited to the direct and solid methods. In connection with these there are no new points that did not arise when reviewing their application to feeders. There is, however, one weakness in the solid system that is not of great moment on a feeder, but its presence is very much more likely to cause trouble on a distributor on which there will usually be numerous joint boxes. However well a joint is packed up below, pressure from above will cause it to sink slightly when the ground is filled in. The subsidence of the box is liable to crack the bitumen at the joint of the box and troughing and thus allow water to enter and ultimately cause a breakdown. How true this is can readily be appreciated by mains engineers, who generally find the majority of their faults taking place either at joint boxes or in close proximity to them.

Distributor cables, even more than feeder cables, should, wherever possible, be laid under the pavement. The advantages gained by so doing are many, the most apparent being :—.

(1) All service cables are shorter and therefore cheaper.
(2) Owing to the absence of heavy traffic over them they can be laid much less deeply, depths of 12 in. to 18 in. being as a rule sufficient, resulting in less expensive trench work.
(3) The ground around the cable is usually drier.
(4) Repairs are cheaper.
(5) More room is obtained, as gas, water and sewage mains are usually all in the roadway.

TABLE 5.

Cost of laying $0 \cdot 2$ *sq. in.* $\times$ $0 \cdot 1$ *sq. in.* $\times$ $0 \cdot 2$ *sq. in. distributors per* 100 *yards.*

Type of ground surface	Lead-covered, steel-tape-armoured, laid direct			Vulcanized-bitumen, laid solid		
	3 single-core cables	3-core cable	Triple-concentric cable	3 single-core cables	3-core cable	Triple-concentric cable
	£	£	£	£	£	£
Sets on a 6-in. concrete foundation ..	213	204	201	260	238	238
Waterbound macadam	128	120	117	170	149	148
Flagged pavement	120	111	108	161	140	139

Costs of Distributors.

Table 5 shows the comparative costs of laying distributors under different types of ground surface, while Table 6 gives the approximate depths of track that have been allowed for in each case.

TABLE 6.

Depth of Track for Distributors.

Type of ground surface	Cables laid direct	Cables laid solid
Sets on a 6-in. concrete foundation ..	2 ft. 0 in.	2 ft. 6 in–3 ft. 0 in.
Waterbound macadam	2 ft. 0 in.	2 ft. 0 in.
Flagged pavement ..	1 ft. 3 in.	1 ft. 3 in.

It will be seen from these figures that there is very little difference in the costs of three-core and triple-concentric distributors, whatever difference there is being due to the slightly higher cost of the three-core cable. There is thus no financial justification for the preference of the triple-concentric cable, with its inherent disadvantages.

The distributor made up of three single-core cables involves rather more expenditure than either of the other two, though this extra cost detracts very little from its manifold advantages, and, for the reasons already explained, the additional outlay is fully justified.

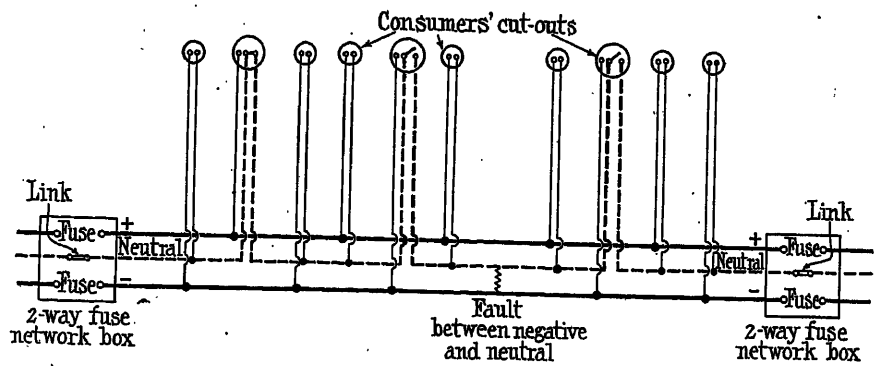

FIG. 5.—" Looped-neutral " services.

As previously stated, the chief factor in determining the size of a distributor is the maximum voltage-drop allowable so as to comply with the Electricity Commissioners' regulations of ± 4 per cent variation in voltage. It is not, therefore, generally possible to take much

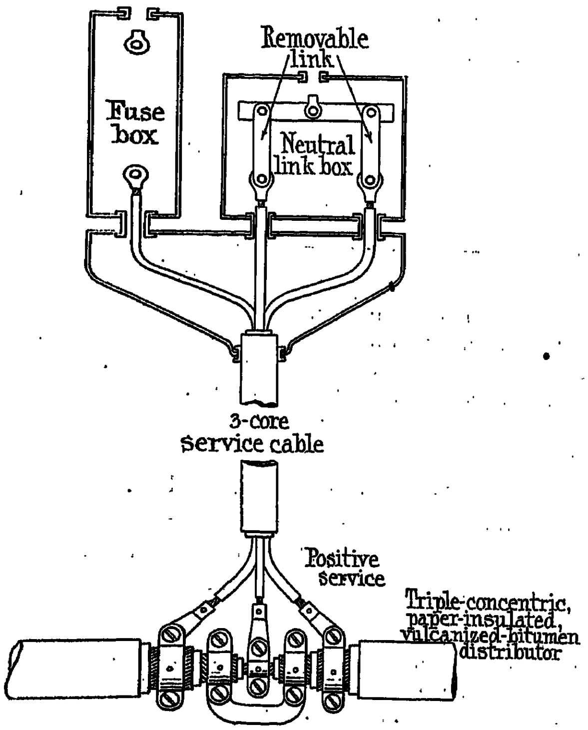

FIG. 6.—Connections for a "looped-neutral" service using a 3-core service cable.

advantage of the higher permissible current-carrying capacity of single-core cables, but it is well to remember that this good quality is a useful stand-by in cases of emergency when overloads may be temporarily thrown on to a particular distributor due to a breakdown at some other point of the network.

LOOPED NEUTRAL SERVICES.

While dealing with the subject of distributors it might not be out of place to put forward a suggestion which the author considers will greatly facilitate the location of faults on vulcanized-bitumen triple-concentric distributors up to about 0·2 sq. in. cross-section, and help to preserve the continuity of supply under fault conditions.

As faults on modern cables are usually due to external causes, the majority of faults on a triple-concentric distributor are between the middle and outer cores, i.e.

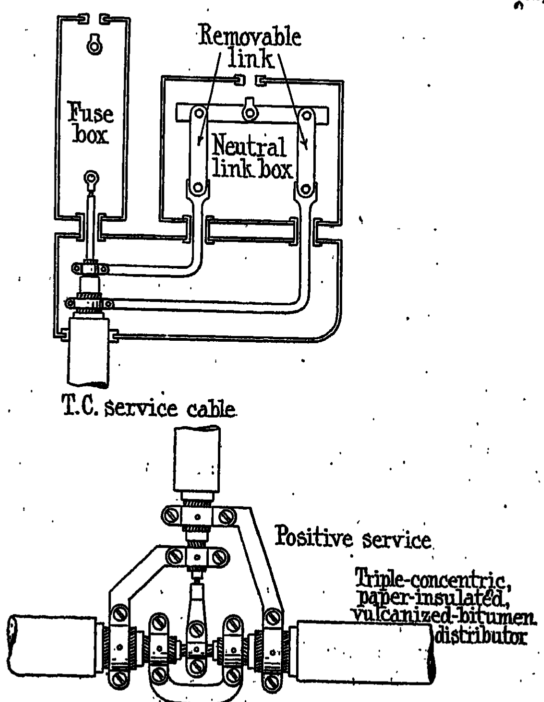

FIG. 7.—Connections for a "looped-neutral" service using a triple-concentric cable with the inner core alive.

between negative and neutral. This being the case, it is only necessary to cut the neutral core to enable a test to be taken that will show in which direction the fault lies.

If the neutral of the distributor is looped in at several of the services along its length, a convenient method of breaking its continuity is provided without any exca-

vating being necessary, thereby effecting a considerable saving in time and money (see Fig. 5). The fault having been traced to a position between two consumers in whose premises the neutral is disconnected, the supply can now be restored to all the consumers with the exception of those tapped off the faulty length. If the fault be between all three cores the positive and negative cores should be bridged at the network box and only one fuse replaced.

Where it is decided to adopt this system on an existing distributor that is not already supplying all the possible consumers, it can be installed whenever a suitable service is being laid, so that no scrapping of existing material is necessary.

The increased cost of such services depends upon their length and the size of the distributor, and amounts to from 25s. to £2 for short services. The saving in the event of *one* fault may cover the extra cost of many looped services.

Figs. 6 and 7 show the arrangement employing three-core and triple-concentric service cables.

(4) Services.

The type of cable and the method employed in laying the distributors is usually adopted for the services tapped from them. This preserves the symmetry of the network and generally simplifies the connections in the service joint boxes. For this reason, before any particular system for the distributors is decided upon the question of services should be considered.

As in the case of feeders and distributors, single-core lead-covered armoured cables possess the most advantages for services. One advantage of this type of cable is that the risk of fire is greatly reduced. A fault on such a cable inside a consumer's premises has only to blow the light station earth fuse to clear itself. With a concentric or twin cable, however, the heavy street fuses on the distributors have to blow before the fault is cleared, and in the meantime a fire may have been caused. For this reason concentric or twin service cables should be laid with more care inside the consumer's premises, anything inflammable being strictly avoided.

The service joints on single-core cables are simple to make, resulting in an increased reliability which more than counterbalances the necessity of having two or three service boxes for direct-laid armoured cables, in place of the single one used for multicore cables. The time taken by the jointer to fix the additional joint-box does not in practice affect the cost of the service, as a standard time, based on average circumstances, is usually allowed for the completion of ordinary services.

The armoured service is so much easier to lay, under all conditions, than is the vulcanized-bitumen solid-laid service that some undertakings actually connect armoured service cables to old vulcanized-bitumen distributors. This fact eloquently supports the armoured cable's claim to priority.

In the author's experience the weakest point in a vulcanized-bitumen service laid solid is where the cable passes through the outer wall of the building; here it may take a sharp upward bend to the cut-outs. If the wall is thick the difficulty of making a sound job of the troughing may contribute towards the frequent breakdowns that occur at this point on old services, but as bitumen is readily attacked by alkaline salts the lime in the wall is probably the cause of most of the trouble. At all such points the cable should be drawn through small earthenware pipes with suitable bends and filled with bitumen.

Where the service cable has to cross a hard road or any other ground that is expensive to excavate and reinstate, it is advisable to draw a lead-covered cable through small earthenware conduits, in order to lower the cost of repairing faults that might occur on that section. These conduits should be short—not more than 2 ft. in length—to enable the numerous pipes, etc., that are often encountered when crossing a road to be more easily avoided.

For large consumers who cannot afford to be shut down for any length of time in the case of a fault, it is very often expedient to loop a three-core or triple-concentric distributor into their premises so that they can always be given a supply, even though a fault may exist on either of the two sections of the distributor supplying them. This is not necessary on single-core lead-covered systems, due to the freedom from interruptions of supply experienced on such systems.

(5) Conclusion.

Sufficient has now been said of the various types of cables and methods of laying to enable a conclusion to be arrived at as to which is the most suitable system to be laid down, taking into consideration first costs, future extensions, load migration, maintenance and continuity of supply.

For feeders.

(1) Three single plain lead-covered cables drawn into earthenware conduits.

(2) Where future load has not to be provided for and where the feeder can be laid in good soft ground and free from the danger of electrolysis, three single armoured cables laid direct would be suitable.

(3) Where the authorities have not much road space available, a three-core lead-covered cable may be drawn into conduits, but this will forfeit the special advantages of single-core cables.

Where a multicore cable is desired larger than 0·5 sq. in. × 0·25 sq. in. × 0·5 sq. in., a triple-concentric cable is necessary.

For distributors.

(1) Three single lead-covered steel-tape-armoured cables laid direct with tile covering.

In a locality where there is a danger of electrolysis, plain lead-covered cables should be substituted for the armoured cables and laid solid in separate earthenware troughing with tile covering.

(2) Where the feeder system is three-core or triple-concentric, three-core distributors could be used, as most of the advantages of single-core distributors depend upon the whole system being made up of a similar type of cable. Triple-concentric distributors should be avoided.

For services.

A type of cable similar to that used for the distributors. If the distributor is laid solid it is often more convenient to lay armoured services direct in the ground.

The author wishes to express his thanks to Mr. J. S. McCallum of Messrs. Callender's Cable and Construction Co., Ltd., for the trouble he has taken in furnishing him with the prices of cables, etc., used in the foregoing calculations.

APPENDIX.

ECONOMY LAW FOR FEEDERS.

Running cost (in £) of energy lost in cable per annum

= watt-hours lost × running cost (in £) per watt-hour generated

= (R.M.S. current)^2 × No. of hours per annum × resistance of cable × running cost (in £) per watt-hour generated

$$= I^2 \times T \times \frac{2lr}{1\,000} \times \frac{\text{running cost (in pence) per unit}}{240 \times 1\,000}$$

$$= \frac{I^2 rlTd}{1 \cdot 2 \times 10^8} \text{ (in £)} \quad \ldots \ldots \quad (1)$$

Capital charges per annum on extra plant, etc., required to meet the demand of $\frac{2I^2rl \text{ watts}}{1\,000}$

$$= \frac{2I^2rl}{1\,000} \times \text{capital charges per watt of plant, buildings, etc.}$$

$$= \frac{2I^2rl}{1\,000 \times 1\,000} \times \begin{array}{c}\text{cost per kW}\\\text{of plant, etc.}\end{array} \times \begin{array}{c}\text{percentage allowable}\\\text{for capital charges}\end{array}$$

$$= \frac{2I^2rl}{10^6} \times C_1 \times \frac{p_1}{100} \text{ (in £)}$$

$$= \frac{I^2rlC_1p_1}{0 \cdot 5 \times 10^8} \text{ (in £)} \quad \ldots \ldots \quad (2)$$

Capital charges per annum on cost of cable and laying

= total cost of feeder × percentage allowable for capital charges

$$= \text{length of cable} \times \text{cost (in £) per yard} \times \frac{p_2}{100}$$

$$= \frac{lC_2p_2}{100} \text{ (in £)} \quad \ldots \ldots \quad (3)$$

where I = maximum current to be allowed for,
r = resistance per 1 000 yards of conductor,
l = route length of cable, in yards,
T = number of hours at which the maximum current I would have to flow to produce the same energy loss in the cable as would take place, during the year, with the usual fluctuating loads,
d = running cost per unit generated, in pence,
C_1 = cost per kW of plant, buildings, etc., in £,
C_2 = cost per yard of cable and laying, in £,
p_1 = percentage to be allowed for capital charges on C_1,
p_2 = percentage to be allowed for capital charges on C_2.

The whole formula now reads:—

$$\text{Total charges (in £)} = \frac{I^2rlTd}{1 \cdot 2 \times 10^8} + \frac{I^2rlC_1p_1}{0 \cdot 5 \times 10^8} + \frac{lC_2p_2}{100}$$

or, as $l/100$ is common in all expressions, the most economical size of cable is obtained when the value of the expression

$$\frac{I^2rTd}{1 \cdot 2 \times 10^6} + \frac{I^2rC_1p_1}{0 \cdot 5 \times 10^6} + C_2p_2$$

is a minimum.

When it is desired to use this formula to ascertain whether or not the installation of a new feeder would be an economical proposition, the following slight variations are necessary:—

Equation (1) should represent the saving in the cost of energy wasted that would be effected by the addition of a new feeder.

Equation (2) should represent the saving in capital charges due to the smaller amount of plant required to cope with the reduced losses.

When (1) plus (2) is greater than (3) a saving would be effected by laying a new feeder of the size allowed for in the formula.

When (1) plus (2) is less than (3) the capital charges on the cost of the new feeder would outweigh any saving due to a higher resultant efficiency.

DISCUSSION BEFORE THE INSTITUTION, 8 JANUARY, 1925.

Mr. W. E. Highfield: I agree generally with the author's recommendation that feeders should be lead-covered cables drawn into conduits. I should not go so far as the author does in adhering to three single cables, because I think the three-core cable has much to recommend it. In town areas, where the load can be fairly accurately estimated, three single cables are advantageous to use. In a growing area, such as is exemplified in the paper, one presupposes a considerable amount of suburban property, probably dwelling houses, with roads of macadam or asphalt. Under such conditions it is not only impossible to estimate the growth of the load but it is equally impossible to estimate the load centre. Consequently, when extensions are required, it is not necessarily a question of just strengthening the cable; it may mean running another cable along a new but adjacent route. I think that the author overstresses the value of the cable loadings. The loading is not always settled by the full-load ratings. With a booster on each feeder the

full-load ratings might be reached, but in practice the most that can be obtained is two voltages from two sets of busbars and this forms a determining point. The author alludes to the difficulty of pouring bitumen without air bubbles in it. Bitumen can be poured without air bubbles if a sprinkling of sharp sand $\frac{1}{16}$ in. thick is laid in the bottom of the trough. The hot mixture, as it is poured in, explodes any moisture into steam, and the sand provides, momentarily, a path for the escape of this steam. I have had samples of mixture, poured in this way, that were quite solid and able to withstand 120 000 volts (a.c.) on a thickness of $\frac{1}{2}$ in. For distribution I prefer lead-covered cable to the armoured type advocated by the author. Armoured cable is difficult to handle, and it is also difficult to remake the continuity of the armour once the latter has been cut. It is impossible to clamp straight on to the lead and possibly the best way is to slip a ferrule under the steel and clamp on to that. The system depends almost entirely on the type of box used, and that is not described in the paper.

Mr. H. A. Ratcliff: There are frequent references in the paper to the permissible loading of cables; but in the case of cables laid in town streets there are frequently so many factors involved that definite loading values are practically indeterminate. Fortunately, however, in the case of low-tension cables this is not of much consequence, since the loadings are limited by other considerations to values which are usually well within those based on the maximum permissible temperature of the cables. There is a possible exception in the case of vulcanized-bitumen cables, owing to the risk of decentralization of the conductor; but cables of this type are now rarely employed. In the case of either three-wire d.c. or four-wire a.c. distributors I strongly advocate the use of a neutral conductor of the same sectional area as the outers. In the case of feeders, however, as the neutral conductor only carries the resultant out-of-balance current, and, moreover, as there will usually be at least two feeders to any section of the network, a neutral conductor having half the sectional area of the outers is permissible. Experience has fully justified the use of the larger neutral conductor, since more complaints of low pressure arise from bad balancing than from actual pressure-drop in the distributors, and further, in the case of heavy network currents arising from short-circuits on the system there is less risk of damage to cables beyond the immediate vicinity of the fault when all the conductors are of the same sectional area. The reference to the shifting of the nodal points on a network is very interesting as the experience is by no means an uncommon one. The reason for it is not always very obvious, but it is probably largely due to certain industries becoming more or less localized, and the fluctuations in trade not occurring simultaneously in the different industries. Effects of this nature were much accentuated by the conditions prevailing during the war. The outward migration of the population usually results in an increase of the load in the central area, due to the conversion of houses into business premises or factories. The determination of the most suitable size for a feeder is, as the author states, largely an economic problem; but electrical problems also arise in connection with the maintenance of pressure at the feeding point and the provision of suitable regulating apparatus. It is always advisable, if possible, to avoid an undue multiplicity of busbars and boosting arrangements. For this reason expediency is usually the most important factor in feeder calculations, and as a rule it pays to provide a feeder of ample size for the probable requirements of the locality concerned. Unfortunately it is not always sufficiently appreciated that feeder losses are essentially peak-load losses, and hence relatively very expensive. The consequence is that in many cases the money spent on peak-load plant and the incidental complications might with advantage be put into the feeders. In connection with the economy calculations the factor T in the author's calculations appears to be rather cumbersome, and usually in calculations of this nature it is more convenient to introduce the load factor of the copper losses. For an average daily load curve, if F is the load factor of the load, it is usually sufficiently accurate to assume that the load factor of the copper losses is $F^{3/2}$. If provision is to be made for a subsequent increase in the size of a feeder, the better plan is to lay the initial feeder of half the ultimate size, and at a later stage to draw in another feeder of equal capacity. This provides a greater carrying capacity in case of emergency, there is less risk of total failure, and if necessary half the feeder can usually be disconnected for testing or repairs. The question of direct laying versus conduits is a very debatable one. The laying of conduits in city streets is frequently attended with many difficulties, and although conduits admittedly possess many advantages for feeders, telephone cables and pilot cables, they have very few real advantages in the case of distributors. Unless conduits are very well laid, lead-covered cables are very apt to fail at the duct joints, and a further possible disadvantage of conduits is that they provide facilities for the passage and accumulation of water and gases. Where it is possible to use them, steel tubes in some cases possess advantages and, furthermore, they provide an additional protection against troubles arising from electrolytic action. Wooden troughing cannot be too strongly condemned; it very soon ceases to support the cables in any way, and, when it commences to rot, the resulting organic acids have a detrimental effect on the cables. Experience has shown that true electrolytic action due to stray currents is of comparatively rare occurrence, and troubles of this nature are usually due to direct chemical action, frequently of a catalytic nature, and also occasionally to electrochemical actions arising from leakage from the cables concerned, as the result of mechanical damage. It is, therefore, essential that all cable sheathings should be effectively bonded and earthed at suitable points. As there is no reference to this requirement in the paper, the author's view on the subject would be interesting. His condemnation of wire-armoured cables in ducts is rather surprising. Wire-armoured cables possess some advantages when drawn into conduits and, moreover, the British Electrical and Allied Industries Research Association recognize an increased loading for cables so armoured. Where it is

possible and economically sound to use them, single-core cables are preferable to either three-core or triple-concentric cables, except in the smaller sizes, when the increased diameter and mechanical strength of a multi-conductor cable is a distinct advantage. Unfortunately the author's case for single-core cables is largely based on the assumption of unduly high current densities. Triple-concentric cables possess many disadvantages and only one real advantage, which arises from the possibility of making the positive conductor the outer, and the neutral conductor one of the inners. With this arrangement of conductors, earth faults on the negative and neutral conductors are impossible, osmotic troubles are entirely eliminated, and the comparatively rare earth faults on the positive conductor can be quickly located.

Mr. L. W. Perryman: The author speaks of a testing wire as a means of locating a fault; this is equally applicable, I think, to triple-concentric cable systems. I do not agree with his view that the triple-concentric cable is the worst of the three forms enumerated; I believe it to be the best as it is far more compact and there is but one cable to lay instead of three. In the case of single-core cables there are three to lay, requiring far more space, and it is important to note that, in towns especially, space is very limited, and for this reason armoured cables laid direct are certainly the most suitable type for getting round obstructions. The author points out that if he gets a fault on one of his outers, either positive or negative, he can, by opening his neutral at two points where he takes it into the consumer's premises, isolate the faulty section of his network and so maintain the normal supply to the rest of the system. That is so. On triple-concentric networks faults are cleared, either by the fuses blowing in the street boxes or being removed on either side of the fault; also some indication is given at the time on the earth-current ammeter at the station and thus gives a warning. Even if the fault develops, the currents going to earth are a minimum. With single cables laid in the ground a short distance apart, however, it is possible to have either the positive or negative main leaking to earth and for currents of considerable value to traverse the ground and produce electrolytic action on gas and water mains, and damage to Post Office wires, etc. In general I think that, except perhaps in special cases, the concentric system throughout is the simplest method for both feeders and distributors. The main advantage of single cables, from my point of view, is that new consumers can be connected without disturbing the old ones, as each of the mains can be jointed singly; the same can be done on triple-concentric cables, but it is not advisable and I believe that the practice is being discontinued.

Mr. E. Ambrose: The author states that the size of the three-core cable is limited to 0·5 sq. in. This is, however, quite a large section for a distributor, and I do not think that there are many instances where it would be necessary to use a larger cable. He also mentions the advisability of making trial holes before laying conduits, but that applies also to cables laid on the solid system and to some extent also to cables laid direct. If cables have to be laid in a road which is likely at some not very distant date to be widened, there is everything to be said for laying them in conduits, because when the road is ultimately widened it may be possible to put the cables under the footway. It is only necessary then to lay the new distributors under the footway and draw out the old ones from under the road. The author advises the draining of conduits and making arrangements for a fall into the manholes. It might even be possible to discharge them into the Corporation drains, but then some sort of non-return valve would be necessary. Very often in a new district that has not been thoroughly drained, the conduits will act as the drain, and so long as the water does not lodge anywhere I do not think that very much damage is done. Regarding his objection to the use of lead-covered and braided cables drawn into conduits, I think that, providing a conduit of not less than 3 in. internal diameter is used, there will be no difficulty in withdrawing the cable, even if the braiding does rot. I have experienced no trouble of that nature. The author speaks of cables laid on the solid system. The great disadvantage of this system is that the work cannot be done very well in wet weather. Another disadvantage is that if the cable is being laid on a hillside, all the compound may collect in the valleys. Again, extra care must be taken to see that moisture does not get into the troughing. It is very difficult to get bitumen to adhere to earthenware in such a manner as to ensure that no moisture is present. In speaking of distributors the author says on page 342 that three single-core, lead-covered cables form the best arrangement from the point of view of continuity, because a fault can occur on one core without either of the others being affected, a rare occurrence on a multicore cable. If he means a fault on, say, the negative of a multicore cable, assuming the negative to be the intermediate conductor on a triple-concentric, perhaps he is correct; but, as Mr. Perryman said, it is possible to get a fault on the outer or earth conductor without necessarily having a fault on the intermediate or inner conductor. I do not, however, agree with Mr. Perryman that the moment a fault occurs on the outer or neutral conductor it is indicated on the station earth ammeter, as unless there is some leakage on either the positive or negative there should not be any reading. It is the usual practice on a triple-concentric system to make the inner conductor positive, the next conductor negative, and finally the outer conductor the neutral. The author advocates a reversal of this procedure, and there is something to be said for this arrangement—the neutral conductor, which carries the least current, is situated where it will not do much heating. At the same time, however, any water that may enter the cable will be driven by osmotic action towards the centre of the cable. I do not like the author's method of earthing the neutral bar at the station or substation. I suppose the switch is closed first on one graduated fuse, and, when that blows, on the next, until they are all blown. When this occurs the neutral is probably 240 volts above earth potential. It would be much better to tie the neutral down to earth by a resistance and shunt the resistance with a circuit breaker and ammeter, so arranged that when the current rises above the value

which is to be allowed with a direct earth connection, the circuit breaker opens and connects the neutral to earth through a limiting resistance. This will at any rate prevent the risk of a 480-volt shock. The author refers throughout the paper to tape armouring, but this is most unpleasant to work. For armouring, it is better to use steel wire. Armouring gives trouble wherever a service has to be taken off, because of the bonding.

Mr. F. C. Raphael: I should like to refer, as previous speakers have done, to the comparison between three single-core cables and triple-concentric cables on the basis of current-carrying capacity according to the figures of the Electrical Research Association. It should not appear in our *Journal*, in the convenient form of a table and uncontradicted, that the cost of feeders or even of distributors is practically the same whether they are three single cables, three-core cables, or triple-concentric cables, because these costs in Table 3, which come out practically the same, are based on greatly different ratings. This is made clear if we refer to the curves in Fig. 1. The table relates to a 500-ampere cable, and it will be seen that the comparison of cost is made between 0·25 sq. in. for three single-core cables, 0·3 sq. in. for the three-core cable, and 0·325 sq. in. for the triple-concentric cable. That is in the case of cables laid direct to the ground. In the case of cables drawn in, the sectional area taken is about 0·38 sq. in. for three single cables, 0·44 sq. in. for a three-core cable, and 0·51 sq. in. for a triple-concentric cable. If they are compared on those bases their prices may be about equal, but there are very few instances in which cables are rated according to their current-carrying capacity in the case of an ordinary three-wire system. They have to be rated on a fall-of-potential basis, and consequently no comparison can be correct unless it is based on the same sections of the cable, in which case the triple-concentric cable is at a very considerable advantage. This advantage compensates for certain inconveniences met with in connecting up. Then again, the author says that the total annual charge is the cost of the energy lost plus the capital charges on the cable. This is obvious. Kelvin's law, however, goes further and states that theoretically a given cable is most economical when that part of the capital charges which depends on the section of the conductor (not laying charges and so on) is equal to the cost of the energy lost. From a modern point of view the cost of that energy lost must not be taken at so many units at the average cost per unit, but at the cost at peak load, which is a very different matter. I am fully in agreement with the author on the question of vulcanized-bitumen cables. The solid system generally is, I think, getting rather out of date, except in those cases where it may be necessary to have particular protection against corrosion of the sheathing. The objection to wood troughing has already been referred to by a previous speaker, but vulcanized-bitumen cables laid in the old-fashioned iron troughing are even worse. The troughing is made up of comparatively short lengths of iron troughing, laid just inside one another without any bonding except the weight of the sections. When water penetrates into the duct or the insulation of the cable perishes, the current leaks first to the duct and thence, as the bonding is bad and the resistance high in consequence, to the first gas or water pipe with which the duct is in contact, and at this place an arc is set up. Within the past 18 months I have met with at least four cases of pipes of other services being damaged by that cause. Referring to the use of three single-core cables for distributors the author says that, should one of the live cables break down, the consumers connected to the other side will in no way be affected. Is that really his experience? Would not a breakdown of one of the outers cause a rise in pressure on the other outer? The graded-fuse method is quite impracticable; if the fuse blows, one of the outers will be at 480 volts above earth potential and the other outer at zero potential, and this dangerous condition will exist until the matter is put right. There is little to be said against the well-known system mentioned by a previous speaker of the circuit breaker and resistance in parallel, so that the resistance is inserted between the neutral and earth if a fault develops, but too much trust is placed in the earth ammeter. It may sometimes show faults in the neutral, but it cannot be relied upon to do so, and in any case the differences in the reading of the ammeter due to a fault in the neutral will not be so great as those due to a fault on one of the outers. It is by no means impossible, however, to make periodical tests which take into account the insulation of the neutral. I will go further and say that when the Electrical Advisers to the Board of Trade permitted neutrals to be earthed through ammeters they did not relieve the undertaker of the necessity of making the other periodical tests on the network which are laid down in the regulations. The special cable manufactured by Messrs. Callender's is interesting, but I do not know that it has been found very necessary in practice. I do not think that jointers experience any great difficulty in making joints on three-core cables when they are alive—in fact it is a matter of common knowledge that it is very often done. Much has been said as to the way in which concentric cable should be connected—whether the neutral should be the outer or the inner conductor of the cable. Personally, I prefer the neutral to be the outer concentric conductor for reasons which have already been stated. The proper place for the conductor at earth potential is obviously near the sheath. It is a protection, and it makes service connections much easier to carry out; if the neutral is made the middle conductor, both of the others have to be cut through for every service. I am not in favour of the looped-neutral method proposed by the author. I do not see that it will be of much assistance in finding faults, and if great care is not taken in removing the links many lamps will be burnt out. If the method is only intended to be used when the system is dead it is another matter, but in any case it does not seem to be quite a sound plan to bring the main cable in and out of the consumer's premises.

Mr. H. Brazil: I am entirely in agreement with the author when he stresses the importance of continuity of supply, and for this reason I am strongly in favour of single-core cables as against triple-concentric cables, not only because there is less likelihood of short-circuits,

but also because new consumers can be connected without cutting off old ones. In this connection I should like to describe a method which we employ to hasten the restoration of supply after a breakdown. In Fig. A three feeders, A, B and C are shown, connected by distributors in which are placed fuses F. Each feeder has an automatic circuit breaker set at 2 000 amperes, the fuses blowing at 500 amperes. The circuit breakers have no time-lag, and apart from the difficulty of fitting these to the existing breakers I do not favour them, because of the destructive effect on the mains and the possible formation of bitumen gas. Assume that a short-circuit comes on at X and that as a result all three feeder automatics come out, making the whole section dead. If we try to restore one of these feeders

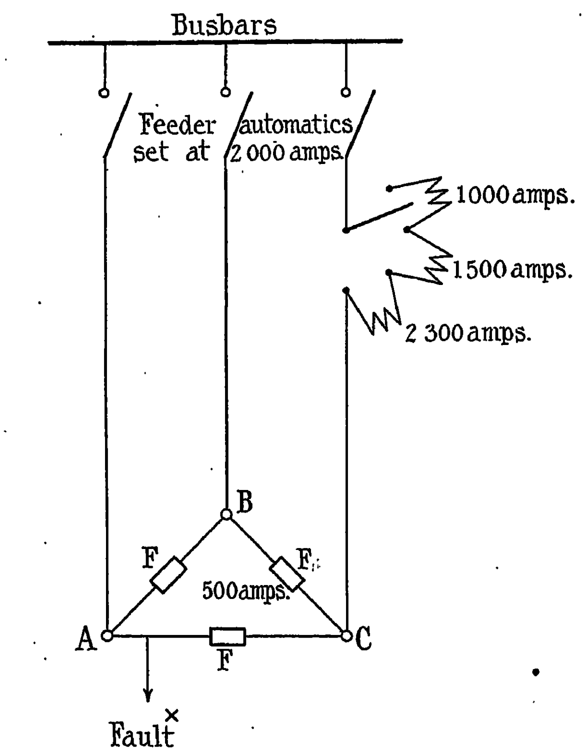

Fig. A.

by closing the circuit breaker, as there is a certain time-lag on the fuses the breaker may come out before the fuses blow, and it will not then be possible for the good feeder area to isolate itself. If, however, a feeder is made alive through the resistance shown, the current on the first or the second step will be sufficient to blow the fuses without causing the circuit breaker to open. When all the resistance is cut out, if the ammeter shows that the feeder is taking its normal load it can then be plugged back on to the bank. If the next feeder tried happens to be the one on whose area the fault is, there are no fuses to blow, and the current will go on rising, until on the third step it will be sufficient to trip the circuit breaker. The operator then knows that this is the faulty area and leaves it dead. The remaining feeders can then be put in in the same way, the faulty feeder area broken up, and sections of it switched on through the resistance in a similar manner. While on the question of quick restoration of supply, I should like to visualize what might be done in the future. Most feeders have three-core pilots run with them, and when one remembers what wonderful things can be done with two wires, in the way of starting up, synchronizing and shutting down rotary converters from a distance, it would appear to be quite simple for three wires to open and close switches controlling distributors situated in the feeder chambers. One can picture the mains engineer of the future sitting in an office with rows of push-buttons in front of him, and ringing the changes until he has, without the help of any jointers, isolated the fault to one section of the distributor.

Mr. J. S. Highfield: The author has invented an ingenious method of testing for faults by taking the two ends of a neutral conductor into a house or premises for the purpose of testing, but I feel that he may find he is in quite an illegal position if he enters a consumer's premises for the purpose of making tests on his own mains.

Mr. J. C. Wigham: I fully agree with previous speakers that in most cases one cannot lay down feeders or distributors, especially the latter, with reference to their heating. It is the voltage-drop that governs the size. This entirely alters the estimates of costs of the different systems given by the author. Further, it alters the costs more than is apparent at first sight, for while, by Table 1, a 0·25 sq. in. single cable carries only 10 per cent more than a three-core cable, yet a three-core cable to carry the same current as the 0·25 sq. in. single cable is 0·3 sq. in.—a 20 per cent increase—and an estimate based on cables of the same section would therefore differ very greatly from that based on heating. There is a point in connection with the use of three single cables instead of three-core cables. To put a three-wire service into a consumer's premises will necessitate three wiped lead joints. This will cost approximately three times as much and take three times as long as jointing a three-core cable. The looped-neutral service is suggested in the paper as a means of facilitating the detection of faults on cables while maintaining continuity of supply. Presumably the author means testing the main while alive, but the neutral wire must not be broken if the outers are alive. What, then, is the use of the proposal?

Mr. P. M. Baker: As I interpret his paper, the author bases the whole of his estimate of cable costs on the assumption that their loading (feeders in particular) is limited by considerations of temperature-rise. This premise is not, so far as my experience goes, justified. The loading of every feeder with which I have had to work has been limited by voltage-drop considerations and is considerably below the permissible temperature-rise for the material. Indeed, it seems to be clear that only on short feeders would it be economical to force the loading up to the temperature-rise limit in a three-wire system, especially one deriving its power from fuel. The effect of the temperature coefficient on the resistance of the cable has not been lost sight of in coming to this conclusion, and Kelvin's law must fix the loading. If this main premise fails, the author's whole case for the use of three separate single-core cables also fails and

the table of cable costs becomes misleading. Further, the whole cost of the cable and its connections must be considered and the service boxes used on three single-core cables must surely be larger, more expensive and involve more labour in installing than boxes for three-core or triple-concentric cables. Careful consideration of costs seems to show that, at any rate in a district in which I am interested, three-core cables drawn into earthenware ducts are the most practical economical propositions both for feeders and distributors as, on cable alone, there is a 10–12 per cent saving over triple-concentric cables of similar section, and reinstating charges are high—frequently as much as 50 per cent of the whole cost of the laid cable. There seems to be little difference in the cost of labour in jointing or making connections to triple-concentric and three-core cables (although jointers seem to prefer triple-concentric), but I cannot say how these costs would compare with those for similar work on three single-core cables.

[The author's reply to this discussion will be found on page 363.]

IRISH CENTRE (DUBLIN), AT DUBLIN, 8 JANUARY, 1925.

Mr. C. P. Coote-Cummins: The permissible current loading given in Table 1, which, I understand, is based upon the result of very exhaustive research, will, I think, be very useful for reference as it is in a very convenient form. The formula given on page 338 is also useful, and is very fully and clearly worked out in the Appendix. I am glad that the author emphasizes the necessity for considering the question of the time in which repairs can be executed. Unless repairs can be carried out in a reasonable time the cost will always be excessive, and this point is too often overlooked. The author appears to favour the laying of plain lead-covered cable in ducts, and Table 4 is a strong argument in support of this, but although I appreciate all that he says I think that the table is apt to be a little misleading, because it should obviously be read in conjunction with Table 3, and in comparing the lead-covered cable laid in ducts with the steel-tape-armoured cable laid direct the former system should be debited with the cost of interest and sinking fund on the increased expenditure during the period which elapses before the extension is required. When this is taken into account the conclusion arrived at might easily be the reverse of that indicated in Table 4 alone.

Mr. A. H. Watson: A distribution network of the sort described in this paper is, I think, more or less a branch of the industry in itself, and one in which an engineer might well specialize. On page 338 the author states that the question of the voltage-drop on such a cable is of only secondary importance, as any variation in the value of this drop can be counterbalanced by an equal variation in the busbar voltage, so maintaining a constant pressure at the nodal points. I do not agree with this; I should consider it bad practice to try to compensate for drop in pressure by varying the busbar voltage, as the loadings on the various feeders might not all be equal, with the result that if the busbar pressure were increased to maintain normal voltage at the nodal point where a cable is fully loaded, the lighter loaded cables would suffer accordingly. The permissible loadings given in Table 1 come as rather a surprise to me as the densities are very much higher than we have been used to in the past. For example, I notice that three single-core cables having a sectional area of 0·1 sq. in. can be loaded up to 298 amperes, which is equivalent to 2 980 amperes per sq. in., and even a 1 in. cable can be run at a density of 1 158 amperes per sq. in. With regard to Fig. 2, I doubt very much whether graduated fuses will work satisfactorily in practice, as it has been found that the behaviour of fuses varies so much according to their condition at the time and the contact at the fixing point.

Mr. P. A. Spalding: In my remarks, I propose to ignore triple-concentric and vulcanized-bitumen cables because I feel sure that no supply engineer would prefer such cables to three-core and paper-insulated cables unless under very exceptional circumstances. On page 337 the author says: "It should be noted that on a three-wire system the neutral conductor carries little or no current." I think, however, that the general experience is that the neutral wire carries considerable current, especially during peak-load periods. If the author has any grounds for expressing such an opinion, why does he provide for neutrals varying in size from 0·125 sq. in. to 0·2625 sq. in. in his figures of cost in Table 3? Clearly he does this because his figures are for standard cables which usually provide a neutral having one half of the sectional area of the outer cores. My own opinion in regard to these cables is that the cross-section of the neutral core need never exceed 25 per cent of that of the outers of a d.c. three-wire system. Anything larger than this is only a needless waste of capital. With a maximum continuous loading of 500 amperes the system would be very badly balanced if the current in the neutral exceeded 100 amperes. For even a moderately balanced system, the current in the neutral, under the loading conditions above referred to, would scarcely be 60 amperes. Therefore, if a 0·25 sq. in. outer will carry a maximum load of 500 amperes, what is the sense of having a 0·125 sq. in. neutral to carry only 60 amperes? On page 338 the author states: "Any variation in the value of this drop can be counterbalanced by an equal variation of the busbar voltage, so maintaining a constant pressure at the nodal points." Here again I must disagree, because, more often than not, regulation of the busbar voltage does not by any means ensure constant pressure at all the various feeding points of the distributing system. On the same page he says: "The use of three-core cables is limited to sizes up to 0·5 sq. in., cable manufacturers being unwilling to guarantee larger sizes." Presumably he implies a 0·5 in.–0·25 in.–0·5 in. cable, and, if so, such a heavy neutral as 0·25 sq. in. would be quite unnecessary, especially as he has already expressed the opinion that the neutral of a cable carries little or no current. For a feeder of this size a 0·1 sq. in. neutral should be ample.

Nine years ago I installed on our system two three-core feeders laid direct, each carrying 0·6 sq. in.–0·06 sq. in.–0·6 sq. in. cables, which have so far given excellent results. The comparatively small neutrals in these feeders have proved quite sufficient. In connection with methods of laying cables, the necessity for considering conduit at all only arises in cases where important cable-runs have to be made along roadways laid with sets on concrete. In such cases, as the author points out, the cost of opening up the road and reinstating the surfaces is a very expensive matter, and to avoid the repetition of such expense a draw-in conduit system may be found necessary. In all other cases, however, and especially where cables can be laid along the footpaths, paper-insulated, lead-covered and armoured cables laid direct are undoubtedly the cheapest to install and maintain. When comparing single-core with multicore cables, the author has made out an apparently strong case for the former, but I consider that his references to the latter type of cable are by no means complete. I am very surprised to find that no reference whatever is made in the paper to the all-important matter of bonding the cable sheathing. In my opinion most of the breakdown troubles on cables—e.g. those due to failure of the protective coverings caused by electrolysis, resulting in premature deterioration of the insulation—have been caused by want of electrical continuity throughout in the lead and armoured sheathings of these cables. I fail to see any special advantage in using "a cable in which is incorporated a thin copper testing-strip lightly insulated from the lead sheathing" (see page 343). Such a cable would have to be specially manufactured and would therefore be costly. Efficient bonding, so easily obtainable with multicore armoured cable, would answer very much the same purpose. I quite admit that single-core armoured cables laid direct provide certain advantages over multicore cables laid direct—when used as feeders—but the drawbacks that I see in the use of single-core cables for distributors are (1) the difficulty of maintaining complete and efficient bonding throughout each run, and of the system as a whole, of the lead and armoured sheathings of these cables; (2) the danger of damage to the neutral cables owing to the relatively small sizes of these in the distributing system, and (3) the extra cost of making service connections, further reference to which I shall make later. With three-wire supplies it is of the utmost importance that the neutral shall be maintained intact and in good order throughout the system, and this condition is rendered far more secure where multicore cables are used because here the neutral core is absolutely immune from any mechanical risk of fracture. The only damage that can affect the neutral of a three-core cable is an internal "dead short-circuit" on the cable itself, but this is such an extremely remote contingency that it need never be seriously taken into account when considering the merits of the respective systems. On page 344, under the heading of "Three-Core Cables," the author states: "The earthing of the neutral through a light fuse is unsuitable with such cables," but I think that the more correct word to use would be "disallowed." Three-core paper-insulated, lead-covered and armoured cables, all laid direct, were installed at Dundalk more than 12 years ago, the cables —with few exceptions—being laid along the footpaths. Although up to the present time upwards of 500 connections have been tapped off these cables, not a single fault has yet developed. Small local faults have, of course, occurred, such as temporary short-circuits or leakages on the street lamp standards and pole bracket fittings, caused by bad weather; these troubles are to be expected under such exposed connections. The worst of these occurrences is a "dead earth" of one or other of the outers due to a fusion of the connections at the neck of a street lamp standard; until such defect can be cleared the effect is a "dead short-circuit" between the outer and neutral (external, of course, to the distributor itself), but the current in such cases is always limited to about 25 amperes by the resistance inserted across the contacts of a circuit breaker between the neutral busbar and the main earth connection at the generating station. Normally this resistance is bridged, but when the leakage current exceeds a certain limit the breaker opens and leaves the resistance in circuit. Thus the neutral can never become open-circuited. On the question of relative cost, at the top of page 342 the author says: "The figures given in the latter table [No. 3] show that three single-core feeders are the cheapest to lay down." Table 3, however, gives the cost of the feeders only, and if the costs of opening up the ground and reinstating as specified in Table 4 are added, the inclusive cost of laying multicore cables is actually less than the corresponding cost of laying three single-core cables. The figures in Table 5 also clearly prove this. I do not question the author's figures in these tables as I presume they are taken from actual practice, but a summation of the figures in Tables 3 and 4 gives the following results as representing the total inclusive cost of laying:—

Type of roadway	3 single-core cables	Multicore cables
	£	£
Sets on concrete	369	366
Waterbound macadam ..	200	197

On the score of inital cost, therefore, I see no advantage in using single-core cables. There are no "exceptional reasons," as the author puts it, why supply undertakings adopt multicore cables for feeder work; it is simply on the grounds of economy, combined with efficiency, that such cable is preferred for both feeders and distributors. At the top of page 345 the author states: "Distributor cables . . . should, wherever possible, be laid under the pavement." I quite agree. It is a pity, however, that he did not include figures of cost under this heading in Table 4. No special difficulties are experienced in making service connections to multicore distributors, and the actual coupling-up is quite easily effected during the dinner-hour, usually between 1 and 2 p.m., when the particular length of cable that is being tapped can be isolated (at the

disconnection boxes) without any inconvenience whatever to existing consumers. The advantage of the single-core cable in respect of facilitating service connections is therefore by no means as evident as the author would have one believe by his remarks at the top of page 344 and again on page 347. I entirely disagree with him in regard to the relative cost of carrying out service connections, and it can easily be demonstrated that, of the two systems, the cost of making services off multicore cable is considerably the cheaper. I should be interested to know whether the author has had any experience of plain lead-covered cables laid in fibre conduit such as is (or was) manufactured by the Key Engineering Co. If so, perhaps he would state whether the lead sheathing of the cables remains as sound in such conduit as it does in the other conduit systems to which he refers in the paper.

[The author's reply to this discussion will be found on page 363.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 14 JANUARY, 1925.

Mr. H. W. Blades: The author in his conclusions recommends the use of lead-covered cables drawn into watertight earthenware conduits. I should like to ask if he has any special recommendations as to making the conduits watertight. It is practically impossible to do this by surrounding the conduits with concrete. One of the chief things to guard against in any conduit system is the accumulation of gas, and the only cure is an efficient system of ventilation of draw-in pits, joint pits and the conduits. Before leaving the question of conduits I should like to ask the author if he has experienced any trouble due to the movement or creeping of drawn-in lead-covered cables, this movement being due to the expansion and contraction of the cables. In this district there have been considerable difficulties due to this, but these have been overcome and it would be interesting to know if the author has experienced any such trouble. The author states that when the feeder can be laid in good soft ground so as to be free from electrolysis, single armoured cables should be suitable. I agree that the factor of electrolytic action must be seriously considered before the decision is made to lay armoured cables direct in the ground. In large cities the feeder cables sometimes not only run parallel with the tramway track but often cut across several tramway routes. There is thus the danger of heavy earth currents being shunted by the armouring of these cables. In Birmingham for the past 20 years it has been the practice for all high-tension lead-covered steel-wire-armoured cables to be laid solid with bitumen in earthenware troughing. In no case can I remember having noticed any signs of electrolytic trouble, and judging from the state of these cables both inwardly and outwardly they are in splendid condition and should last more than another 20 years. With regard to the author's proposal on page 343 for raising the potential of the neutral wire by means of a light copper fuse, I suppose this means entirely disconnecting the neutral from earth and then flashing one of the outers through a light fuse. This is not good practice, and such flashing should only be done through graduated resistances. One of the best-known maxims for the successful maintenance of any three-wire mains system is to keep the neutral wire healthy, and this can only be done by clearing off all incipient faults on the neutral wire. I presume that the author's suggestion for the looped-neutral services will necessitate the laying of a service cable of the same cross-sectional area as the distributor, in order that the carrying capacity of the distributor is not reduced. The service cable shown in Figs. 6 and 7 appears to be of much smaller cross-sectional area than the distributor. This would also seriously affect the accuracy in loop tests for the localization of faults. In an industrial or shopping area it might be difficult to obtain access to the consumer's premises for the purpose of disconnecting the special neutral link, and in a residential area it would be very difficult to accommodate a service cable of the 0·2 sq. in. triple-concentric type. It would therefore be advisable for any disconnecting of the neutral wire to be done in suitable boxes in the street, which would always be accessible day or night.

Mr. N. A. Allen: In making a comparison between single-core, three-core, and triple-concentric cables, it is only fair to do so on a basis of their performance, but it is suggested that it would have been of more use had the more practical method been adopted of comparing on a basis of the B.E.S.A. copper sizes instead of the intermediate sizes chosen, which, as a matter of fact, would never be used. Thus in the first case shown under "Cables laid solid" the areas would be 0·4, 0·5 and 0·6 sq. in., instead of 0·375, 0·44 and 0·525 sq. in. given in the paper. These comparisons have been made on a load of 500 amperes for a 0·25 sq. in. section, but for transmission purposes such a current would give an excessive voltage-drop. Even if a 1·0 sq. in. cable were taken instead of the 0·25 sq. in. chosen, and the drop limited to 20 volts in order to conform with the Commissioners' Regulations for a 500-volt system, the useful length of transmission would be limited to about ½ mile. With reference to the testing-strip type of single-core cable, this is a well-known principle for three-core high-tension cables where one strip does the work for the whole system, but the introduction of a single strip for each core would involve considerable expense out of proportion to the advantages gained. The question of electrolysis due to cables crossing the line of tramway systems has been raised by several speakers and in this connection it is of interest to remember that in the United States, tramway earth currents are regarded as a necessary evil and steps (sometimes very elaborate) are invariably taken to guard against damage to cables through this cause. These consist of the introduction of copper bonds or connecting sheaths and drainage wires at suitable points, these having been predetermined in an "Electrolysis Survey." A point of interest in connection with the use of three single-core armoured

cables, which is recommended in the conclusion of the paper under certain circumstances, is in connection with the possibility, which sometimes occurs, of having to change over from a d.c. system to an a.c. system while using the same cables. In this case, of course, three single cables could not be used, owing to their high inductance, whereas the change could be made without difficulty on the other types of cable.

Mr. R. H. Rawll: There are two points in the paper which interest me from the point of view of the behaviour of consumers' wiring under fault conditions on d.c. three-wire networks. The author describes a system in which the neutral wire is earthed through a fuse at the station. If an earth occurs on one of the outers this fuse will blow and the other outer will be raised or lowered to the full outer pressure, above or below earth as the case may be. It is, of course, true that the Electricity Commissioners require this state of affairs to be remedied within 24 hours, owing to the greater risk of shock to earth. I cannot, however, agree that apart from this consideration "it involves no danger to the electrical system." This may be true if the undertaking's mains only are included in this category, but due regard must also be taken of the condition of consumers' wiring, particularly old installations in wood casing, where in my own experience fires have occurred through this cause. It may, of course, be argued that consumers are responsible for the maintenance of their installations in good condition. But in how many cases is it done? We must face these facts, and distribution systems should be so designed and operated that the liability of excessive pressure to earth with its attendant risks is reduced to an absolute minimum, and if such a contingency should occur it should be remedied with all possible speed. The author also explains that when an undetected earth fault occurs on the neutral cable, should an earth subsequently develop on either of the outer cables a short-circuit will take place between these two faults, and will remain until one of the faults burns itself clear or is isolated by the operation of fuses. Such faults should, of course, be confined to the street mains, but it may be of interest if I describe certain conditions in which a consumer's wiring may take part in such an undesirable short-circuit. Where a consumer takes a considerable quantity of energy from the mains it is often necessary to balance the load as near as possible on either side of the neutral. In such cases three wires are sometimes run from a central distributing point in the premises to the service position, as in Fig. B. No fuse, of course, is permitted in the neutral wire, because any interruption of the neutral without the simultaneous opening of the other two wires would occasion a risk of an excessive pressure across the terminals of those consuming devices, the normal operating voltage of which is half that of the full pressure between the outer cables. Now the insulation of this neutral wire may break down and give rise to an earth fault of such small magnitude as to be undetected. Should an earth develop on one of the outer cables in the street in the vicinity, however, a short-circuit will occur between these two faults, as the author has described, the full current of which, in this case, will pass through the consumer's neutral wire. Owing to the fact that there is no fuse in this wire, this will continue until one of the faults burns itself clear, or the fuses in the network or at the station, which are usually of high capacity, come into operation. It is clear that in either case the results on the consumer's property may easily be disastrous. This is obviously very bad practice, but the number of wiring contractors who are unaware of this fact is surprising. The only safe method is to provide a three-pole circuit breaker with a trip coil on *each* pole; but since this is usually out of the question for a variety of reasons, the system shown in Fig. C should be adopted in all cases. Here the balancing of the load takes place at the service position and, in the event of the faults under consideration taking place, one of the fuses connected to the neutral service cable will blow and thus not only prevent further damage to the consumer's property whilst the other fault continues, but, by reason of the notification to the supply undertaking of the blown fuse, will give an indication of the location of that most elusive of all faults—the neutral fault.

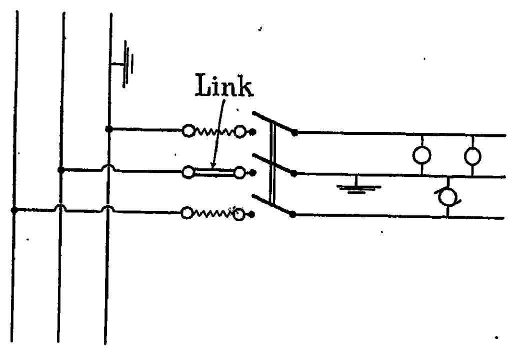

FIG. B.

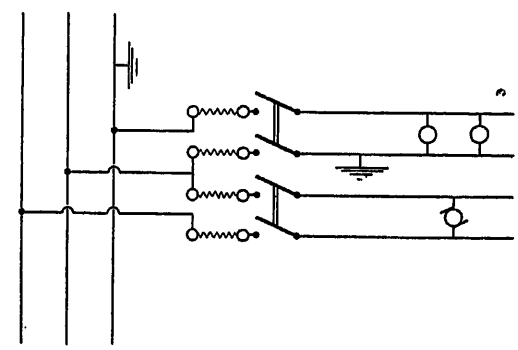

FIG. C.

Mr. A. E. Smith: The solid system of laying cables is recommended where the ground may contain corrosive substances, but the direct system if subsidence is likely to occur. Subsidence is continually taking place in certain mining districts in this vicinity, and the ground is frequently made up with ashes, which are notorious for causing corrosion. What system would the author recommend in such a case?

Mr. F. Forrest: A true comparison of the costs of

various types of distributor cable should combine the figures given in Tables 1 and 5, so as clearly to set out the fact that the cheaper lead-covered cables laid direct are also capable of carrying a higher current loading. I have combined in the Table A particulars with reference to three types of 0·2 sq. in. × 0·1 sq. in. × 0·2 sq. in. distributor cable laid under flagged pavement, using the figures given by the author.

It is evident from the table that the vulcanized-bitumen cable is an extremely expensive type, and where cost is a first consideration there seems to be no justification for its use. The author has not considered the use of plain lead-covered cable without any further armouring. Such cable, so long as it is laid in trenches on soil which has had the sharp stones sifted out of it, and afterwards covered with a protecting tile, should be perfectly satisfactory and still further cheapen the cost. In all cases the bonding of the lead should be very carefully done by means of wiped joints and the cables should be kept more than 3 ft. away from the nearest tramway rail, so as to avoid the possibility of electrolysis due to stray traction return currents. Pilot cables for use with low-tension feeders are really not justified. A more satisfactory means for indicating the feeder-point voltage can be obtained by carefully calibrating the feeder ammeter to read the feeder-point voltage after a careful test of the resistance of the feeder has been made. The looped-neutral system mentioned by the author seems to me to add danger without introducing any substantial benefit. It is quite conceivable that the neutral link box in a consumer's premises might be opened by an unauthorized person and the link removed; this might have disastrous consequences, and for this reason I cannot believe that it will ever be generally adopted.

Mr. H. S. Davidson: The author is strongly in favour of laying three single-core cables as distributing mains. I should be interested to know what type of box he uses when tapping services off such distributors, assuming his intention to be that the service cable should be a three-core cable, and that all the cables used are paper-insulated. Cast-iron boxes do not appear to be satisfactory and the only alternative is a lead "tee" box. This entails the making of seven plumbed joints and is a very tedious and costly method. Has the author considered this additional expense in preparing his paper?

Mr. W. E. Groves: In comparing three-core with single-core feeders it is not generally practicable to carry this comparison above a load rating of 1 000 amperes per sq. in., on account of prohibitive voltage-drop and boosting requirements; this current density represents a voltage-drop of approximately 40 volts on the outers of a feeder 800 yards in length. Full advantage therefore cannot be taken of the higher rating of single-core mains under 1 sq. in. in section. It is therefore, on the score of cost, advantageous to use three-core cables as far as manufacturing limits permit. The use of conduits should be avoided wherever possible, having due regard to street disturbances and the difficulty of accommodating a large number of cables on one route. It is also safer in the case of breakdown than bunching the cables in the ground if several feeders have to be laid close together. The making of trial holes is an obvious preliminary of conduit laying, but unfortunately does not always guarantee a clear course. Although concrete helps in this direction, stoneware conduits should never be regarded as being gas- or water-tight and it is necessary to provide for ventilation and drainage. They are not a safeguard against electrolysis, the evil effects of which are usually concentrated at the conduit joints. Flexibility for joints in conduit pits must be provided for where lead-covered cables are heavily loaded, otherwise expansion and contraction will crack the plumbs of the joints. Apart from their cost there is no sounder system of distributors than single-core paper-insulated vulcanized-bitumen cables run solid in stoneware troughing. They have an enormous advantage for rapid fault localization and repair. Their cost, however, puts them generally out of court for new networks, particularly where road widenings and disturbances are contemplated. In solid laying, care should be taken that troughs *are* filled under all conditions. Wooden troughs are inherently bad. Pilot cables on a three-wire system, apart from their cost, are most unsatisfactory on account of uncertain surface contacts of plug boards and fuses. Ammeters should be calibrated for voltage-drop; this, with a reasonable balance, is a sufficiently accurate measure. The outers of triple-concentric cables should be neutral and the insulation of the neutral should be maintained as on the outers. As in the case of feeders, comparison of costs of different types of distributors based on load ratings of cables is fallacious, very high current densities being generally inadmissible for reasonable "regulation," particularly with developments of heating and cooking supplies. Single-core armoured distributors appear attractive from the point of view of continuity of service, but it is surprising to learn that the service tees are not more costly than for three-core cables. Three-core cables need not be disconnected for jointing,

TABLE A.

Type of cable	Constant current loading	Price per 100 yards	Cost per yard per ampere
	amps.	£	d.
3 single lead-covered and armoured cables laid direct ..	438	120	0·66
3-core lead-covered and armoured cables laid direct ..	390	111	0·682
3 single vulcanized-bitumen cables laid solid	317	161	1·22

but it is risky to joint triple-concentric cables while they are alive. Fuses on distributors should be confined to interconnecting points of feeder networks. In Birmingham simple network boxes are used which permit of any distributor being isolated, solid-linked or fused as desired, the fittings being interchangeable. Tightening of three-core cables is more in evidence with shaped than with circular conductors. The extra cost of the larger-spaced cable would detract somewhat from the economical advantage of the standard cable. The use of conduits for distributors is obviously disadvantageous if frequent services are likely to be required.

[The author's reply to this discussion will be found on page 363.]

North-Western Centre, at Manchester, 20 January, 1925.

Mr. L. Romero: The author's main argument is that single-core cables are better than three-core cables for three-wire networks, solely because the results of faults on three-core cables are more serious than on single-core cables. I do not agree with that idea at all, as I think the author throughout the paper attaches too much importance to the fault question. In my view a modern network consisting of lead-covered armoured cables should have very few faults indeed whether the cable is single-core or three-core; and that view has been borne out by my experience. But certainly I would expect more faults on single-core than on three-core cables, first because far more faults occur on small cables than on large cables, owing to the difference in mechanical strength, and secondly because in the case of the single-core cable there is three times the length of cable to break down, and between two and three times the number of joints. In Salford the three-wire network originally consisted almost entirely of single cables, but about the end of the war, for reasons of economy, we began to use three-core armoured cables laid direct. Since then we have laid about 30 miles of three-core distributor cables and made some 2 000 joints on them. During all that time we have had exactly one fault on a small cable, the results of which were not at all serious. I have also had experience extending over a longer period with concentric cables on the a.c. system, and in this case also faults are of extremely rare occurrence. I estimate that the cost of a single-core network, including services, would be about 12 to 15 per cent higher than that of a three-core network. I feel sure that a similar freedom from faults on three-core networks is experienced in many other undertakings, and I hope that some other mains engineers will give us the benefit of their experience. There is one other disadvantage of putting down single-core armoured cable for a d.c. network which appeals very strongly to me, viz. that it makes it impossible to change over the network to alternating current. We have recently changed over portions of our d.c. network to single-phase three-wire, without re-laying a single yard of cable, and we have other schemes in hand. Of course these schemes would be impossible if the network consisted of single-core armoured cable. Table 1 seems to me very misleading in that the maximum current allowed for the larger cables is much too high. A 1 sq. in. single cable in a nest of conduits cannot be loaded safely above 750 amperes, which is the current allowed by the author for a 0·5 sq. in. cable. Above this limit crystallization of the lead, due to expansion and contraction of the cable, sets in. I agree with the author that single-core cables are to be preferred for feeders, because nothing smaller than 1 sq. in. cable is of much use for feeders on low-pressure d.c. networks, unless they are very small networks indeed. If one did use 0·5 or 0·25 sq. in. feeders, as the author seems to suggest, I am of opinion that three-core cables would be better. The author seems to think that pressure-drops in feeders are of no importance. I do not agree with him. In practice it is usually impossible to keep all the feeding points at the same pressure, due to differences in length and loading of the feeders. I find that a 0·5 sq. in. feeder, 1 000 yards long, loaded to 748 amperes—the figure given in Table 1 for 0·5 sq. in. single-core cable—would give a pressure-drop of nearly 20 per cent on a 440-volt system. Drops of this order must be considered excessive from the points of view of both pressure regulation and losses. I think that pilot cables should be dispensed with altogether if possible. I believe this could be done if instrument makers would only set themselves to design a voltmeter which would indicate the busbar voltage less the feeder drop. If they would do this, I believe that most undertakings would install these voltmeters and scrap their pilots. An instrument is required with three coils instead of one; one coil for the busbar voltage, one for the outer voltage-drop, and one for the neutral voltage-drop. An instrument of this type would give a direct reading of the voltage at the far end of the feeder, the pilots being dispensed with altogether. As an alternative I should like to suggest that feeder ammeters should have their scales marked in voltage-drop in the feeder on one side and in amperes on the other side. The switchboard attendant could then easily calculate the voltage at the feeding point. Both these suggestions seem so simple that quite possibly they have already been carried out, though I have no information on the point. The author's suggestion for cable with a testing strip to facilitate the location of faults seems to me totally unnecessary for the reasons already given. The author's scheme for looped-neutral services on vulcanized-bitumen triple-concentric distributors is ingenious, but in my opinion the money would be better spent in replacing the distributors with three-core lead-covered cables. If there are so many faults as to make it necessary to carry out all these expensive precautions, I think that the cables should be relaid altogether. Although I do not believe that it ever pays to run additional feeders, it has nevertheless to be done because the existing feeders become overloaded and because satisfactory pressure must be maintained. I do not take exception to the author's figures in Table 5 but I should like to ask him whether

he has included in the cost of the lead-covered steel-tape-armoured cables, laid direct, the extra cost for the transport and labour with three cables instead of one, and the extra cost for protective boards or tiles. In regard to the author's statement that trouble has been experienced due to the straining of the cores of three-core cables when opening them out for making service joints, I have not experienced any trouble of that sort and I do not think it is likely to occur on properly designed cables.

Mr. A. J. Lovell: Several points the author has not mentioned may appreciably alter the comparison of costs of different systems. In the case of cables laid direct, the ease with which holes may be bored with one of the hydraulic borers on the market, and cables drawn in across busy thoroughfares, and the resulting saving in excavation, heading, driving and reinstatement, would materially alter the estimates. For example, the first 320 yards so laid in Manchester showed a saving of £339, or about £1 a yard. The author does not mention the use of pass-through boxes on duct lines, by which levels may be altered to avoid pipes, and so avoid laying the total length at any great depth. This is an important point in large cities where pipes are numerous. I do not consider that the concreting of earthenware ducts laid at depths of 2 ft. 6 in. to 3 ft. in the roadway is necessary. Reinforced concrete slabs placed above are a convenient protection against picks, though such protection is not generally necessary. On page 340 the author mentions watertight conduits. In my experience I have never known of a length of duct line in wet soil which might reasonaby be called water-tight. Because of this percolation of water and the risk of acid entering with it, I favour the drawing-in of armoured, lead-covered, jute-served cable. The expansion and contraction, and consequent creeping of cables, calls for secure anchoring at every box, and frequent inspection, so that maintenance costs become a considerable item. Duct lines can only be profitably used in congested areas where frequent street excavations must be avoided. On page 340 the author says: "Modern practice is to use earthenware troughs . . . because better joints are possible between two troughs." Personally I consider that if there is any feature that condemns earthenware troughing it is the joints, unless the author is referring to the use of lock joints. Several have been devised, but none, I believe, has been sufficiently tested. Though wood troughing has many serious disadvantages there is much to be said for its mechanical strength when joints are made to butt and are surrounded with a cast-iron trough box with cover bolted down, as used in Manchester. I have known a subsidence to take place, and a length of troughing containing a joint to support the ground above without buckling over a span of 10 ft. This could not be said of an earthenware trough. Intimately connected with the type of trough is the question of depths. In Table 6 the depth under flagged pavement is given as 1 ft. 3 in. I doubt whether the local authority would permit this depth, apart from the difficulty of avoiding gas services and the risk of fencing pins at some later date piercing the troughing so near the surface. As no general rule can be laid down for mains work—no two jobs being alike—each must be dealt with on its own merits. More trouble is caused by vibration than by crushing at ordinary depths, and the nature of the road traffic should be one of the deciding factors. Generally speaking, cables laid solid should be deeper than those laid direct, owing to damage at troughing joints due to vibration. I do not agree that troughing and service boxes will sink when the ground is filled in. If settlement does take place it is due to bad workmanship. With regard to triple-concentric cables, theoretically, from the point of view of heating, the neutral cable should be the inner conductor, as it carries the least current, but often the practical requirements outweigh the theoretical advantages, and in this case the outer is usually made the smallest conductor for increased flexibility. I do not agree with the author that this is a disadvantage, as he points out on page 345, where he says that in the event of the cable being damaged by a pick no indication would be perceived at the station for some months. If no network insulation resistance test is ever taken at the station I can quite believe it, but I do not think that any mains engineer would rely merely on the earth ammeter readings. Frequent tests should be taken at the station, and the resulting figure in ohms will at once show up a neutral fault, when steps can be taken to locate it. That the outer conductor is the neutral is, in fact, a decided advantage, for a neutral fault can be located with much less risk of interruption of supply. On page 337 the author says that the neutral conductor on a three-wire network carries little or no current, and Table 1 shows that the sectional area of the neutral is half that of the outers. In these days of cookers, radiators, and domestic appliances, the diversity of the load, which is not under the control of the engineer who makes his balance sheets, may give rise at times to considerable out-of-balance current in sections of the neutral. I have known the current in the neutral on a normally balanced section to be 150 per cent in excess on a cold and changeable day, due to the varied use of radiators and lighting. Again, if the supply to one outer be interrupted the neutral will carry the whole current of the other outer. In large modern networks it is desirable to run neutrals of the same sectional area as the outers; the cost of the increased copper is partly offset by the reduced pressure-drop and the immunity from damage to the neutral caused by excessive overloading under short-circuit conditions. I agree with the author that the disadvantages of triple-concentric cable rule it out for use on modern networks. I do not, however, agree that it is necessary to make the cable dead for jointing, either on concentric or three-core cables; my experience of jointing is that if carried out by well-trained jointers the joints are as reliable as, if not more reliable than, the cable itself. The best type of cable to use is undoubtedly that which gives the surest continuity of supply. In Manchester there is a very large amount of three-core and four-core distributors. Over 10 000 joints are made annually, about 75 per cent being on three-core and four-core cable; and so far I have not known one fault to occur. Jointing of all kinds is done while the cables are alive, and with well-trained jointers and careful

supervision no difficulties are experienced. Thus there is no interruption to supply. This, I think, proves the case for a three-core network. I agree with the author in so far as where distributors larger than 0·5 sq. in. are necessary, a single-conductor continuous lead system is preferable, and full advantage can be taken of the reduced current density permissible in the larger cable.

Mr. H. M. Crellin: It is by no means agreed that the current densities shown in Table 1 are acceptable as safe figures. The densities given imply that the final temperature of the cables will be of the order of 150° to 160° F.—possibly more in some situations—and this, in my opinion, is too high. The effect of these high temperatures on the voltage-drop should not be overlooked when working out sizes of cable conductors. The drop at the temperatures I have mentioned will be 20 to 25 per cent more than that calculated on the copper resistance figures given in the B.E.S.A. tables for 60° F. Allowing for this, the voltage-drop for some of the sizes and densities indicated in Table 1 will be as much as 18 volts per 100-yard run. I do not know of any undertaking which could endure this drop on either feeders or distributors. On page 338 the author says: "The choice of the size of cable for a feeder is more an economic than an electrical problem." I think that in 99 per cent of the schemes I have had to work out the sizes have been entirely decided by the question of the voltage-drop. Speaking generally I should say that the advantage of single-core cables would be most marked in the case of feeders on large undertakings, where heavy currents have to be provided for, the advantage of large single-core cables being in the much greater lengths of cable that can be conveniently handled, compared with the comparatively much shorter lengths of three-core cable of the same sectional area per core. The author refers to the use of a "copper testing strip" on single-core cables. From the point of view of cost I doubt whether it would be considered a practical proposition in most cases, but if it is a practical proposition for single-core cables I should say it is far more so for three-core low-pressure cables. The extra cost, of course, is due to the cost of the copper test sheath and the comparatively thin insulation between it and the lead sheath. That extra is a far bigger item on a small single-core cable than on a large three-core cable. While the cost might be about 30 per cent on a single-core cable, it would be less than half that on a three-core cable. With reference to the statement attributing trouble on three-core distributors to the straining of the cores when they are wedged apart for jointing on services, a certain borough electrical engineer some 20 years ago always ordered three-core cables for low-tension work to be made having the same thickness of dielectric as on his 6 000-volt cables, stating that it paid to have the increased thickness on account of the greater facility for jointing services and greatly reduced risk of damaging the cores by straining them apart. On page 344 the author discusses the disadvantages of triple-concentric cables, referring in particular to the smaller sizes, and in this matter I am in full agreement with him. One of the greatest disadvantages of that type of cable is its mechanical weakness. To give the requisite area, the intermediate and outer conductors are composed of a comparatively large number of fine wires (or thin strips) over which are placed the (comparatively) heavy thicknesses of dielectric, the final result being a cable containing a large amount of insulating material and very little copper—a not at all desirable type compared with the equivalent three-core cable.

Mr. A. B. Mallinson: I am rather surprised to find that the author has given no indication as to the prices of copper and lead at the time at which he took out the costs. That, I think, is a very important factor. The price of lead, for instance, has risen nearly 50 per cent during the past year. The value for reference purposes of the tables given in the paper would be greatly increased if this information were added.

Mr. H. C. Lamb: On page 343 the author recommends that the potential of the neutral wire should be periodically raised to that of the outer, with the object of detecting faults. This was tried in Manchester some years ago, but had to be given up because it was followed by many faults on installations, and, in one or two cases, I believe, fires actually broke out as a result of these faults. On page 345 the author says that there is no particular advantage in laying distributors in ducts. In large towns, I think, there is often a considerable advantage, because (particularly in crowded streets, such as Market-street and Piccadilly in Manchester) the spaces under the footpaths are full, and distributors frequently have to be laid in the roadways. The author says that concrete is a very good protection against men with picks. I agree that it should be so, but our experience in Manchester has been that navvies break through it.

[The author's reply to this discussion will be found on page 363.]

Scottish Centre, at Glasgow, 10 February, 1925.

Mr. J. Henderson: There can be no doubt that the best system of laying for feeders is the draw-in system, more especially for a growing load. For a dense city area my preference is for three-core distributors, lead-covered and laid solid. To lay cables solid appears to be the best system in such a case, and direct laying could not be considered. With large and congested tramway systems electrolysis would be almost a certainty and trouble would ensue. The usual system nowadays is to adopt alternating current with four-core cables laid direct in outlying districts. For services the cheapest method consistent with reliability should be used and twin, lead-covered armoured cables appear to give the cheapest service. I certainly disagree with the author that it is necessary to make a triple-concentric cable dead to give a service, and I do not think it is ever done. The "looped neutral" idea looks very attractive, but it may lead to more trouble than it is

worth, and it looks probable that most of the faults might be located in the joint fittings. The author is scarcely consistent in his comparison of costs. He has allowed for the current-carrying capacity of the cables in his tabulations, but on page 346 he states that this can scarcely be taken advantage of due to the permissible voltage-drop. Likewise, mains engineers will be influenced in the steps taken to give further supply to an outlying district, not by the author's equations given in the Appendix but by the permissible voltage-drop and the complaints of consumers.

Mr. C. E. Shaw: I am not in agreement with the author's suggestion relative to triple-concentric cables, viz. that the outer conductor of the cable should be made positive instead of neutral, as is the usual practice. Practically all cable faults, and a large percentage of joint-box faults occur, in the first place, as neutral faults, which may exist for some time before the cable actually goes out of commission. A study of the earth recorder chart will often, but not always, reveal the presence of a neutral fault, and if prompt measures are taken it is possible to locate and repair the fault before it actually causes an interruption of supply. If the positive pole were to form the outer conductor, it is obvious that a fault would develop so quickly that the cable would be interrupted before the fault could be located.

Mr. A. McLennan: I agree with Mr. Henderson that it is quite unnecessary to make cables dead when jointing. This does not strengthen the argument in favour of three-core cables.

Mr. D. Berry: The problems in connection with cable laying and distribution vary considerably with different undertakings. Local conditions and size of supply system affect the point of view, and one hesitates before stating definitely that this or that system or method is the best. I propose to consider the paper mainly from the point of view of the application of the methods favoured by him to a distribution system in a large city such as Glasgow. He treats first of feeders and states that the voltage-drop is only of secondary importance. This may be so where multiple busbars are used in the generating stations, but in cases where one busbar voltage only is maintained the voltage-drop is of primary importance. With regard to the formula on page 338, I think that it will generally be found advisable to select the suitable size of feeder mainly on an empirical basis, and to err on the large side. The author indicates a preference for single-core cables but I do not share his enthusiasm for these against multicore or triple-concentric cables. He admits that space is a determining factor in a consideration of the type of cable to use, and in a large city where almost every inch in the streets and pavements is valuable the claims for triple-concentric feeders are strong. This is especially so when 1·0 sq. in. feeders are used, as three-core cables, as explained by the author, are inadmissible. For instance, a section pillar with three feeder ends—one feeder and one looping in—and 10 distributors would require 39 single cables. I think that the author claims too much for the draw-in system for feeder laying. There may be small zones in which, for special reasons, it is advisable to lay ducts, but as a rule the exact route of further feeders is uncertain, and if ducts are laid they may never be used. Fortunately, feeder faults in Glasgow have not been numerous, but in any case it is by no means certain that the average cost of locating, drawing-out and replacing a length between manholes will be less than that in faults on feeders laid solid. I agree with the author as to single bitumen cables, partly, among other reasons, for the one he gives, viz. the danger of damage resulting while the fault is in its incipient stage. His contention that the choice of the type of distributor cable is very rarely affected by the maximum carrying capacity does not hold if the distributors are short, as is generally the case in large cities, where voltage-drop is, as a rule, of secondary importance to current-carrying capacity. Three-core lead-covered cables laid direct or triple-concentric cables laid solid (depending on circumstances) will, I think, be found to be more satisfactory generally than single lead cables. Direct laying is the fashion, but while the long life of a direct laid cable has not yet been proved, its advantages in speed of laying and low cost are very tempting to the mains engineer. The author's objections to the danger of jointing with triple-concentric cables alive is probably based on experience with the use of link fittings as shown on Figs. 6 and 7. With shell-type fittings, triple-concentric joints are made with the cable alive every day, and I have known jointers more ready to work with triple-concentric cables alive than with the tightly formed three-core or four-core cable in vogue. The author's suggestion of a looped-in neutral for triple-concentric distributors will not always be so satisfactory as he suggests. Apart from the introduction of a possibly dangerous break in the neutral, the localization of a fault may not be clearly defined if intervening consumers' switches are closed, and it may be that one cannot obtain access to the premises with the looped-in neutral joint when it is desired.

Mr. H. M. Stronach: The author deals with single-core, three-core and triple-concentric cables for feeders, distributors and services on a maximum-current basis and arrives at what he considers to be the ideal combination, viz. single lead-covered cables throughout. Every city has its own special circumstances, but to ignore the length of feeders by running at different pressures to overcome voltage-drop, allowing for voltage-drop in distributors, and providing ducts for feeders, suggests one station, the load going for some length in one direction, the feeders being short and the distributors comparatively long. In a town with 50 000–60 000 kW of d.c. load supplied by a number of substations from 2 000 to 6 000 kW capacity, the duplication of rotary converters, busbars, etc., in each substation to allow two or more pressures to be supplied to feeders would make this impossible. With 1 sq. in. feeders running at a fixed pressure with a maximum load of 750 to 800 amperes, the effective length is 400 to 500 yards, and in these circumstances single cables laid in any manner are more expensive than triple-concentric cable. The question of space also arises. The question of ducts is a very serious one. The author mentions the shifting of load, and no more expensive job can be conceived than laying ducts and then finding that they either

cannot be used at all or can only be used by increasing the length of cable necessary. Distributors are generally comparatively short, and the load starts to drop immediately they leave the feeding point. Therefore if the pressure is maintained at the feeding point, voltage-drop can be ignored except in exceptional cases. The author condemns triple-concentric network. Glasgow has roughly 400 miles of such network, both lead-covered cables and vulcanized-bitumen cables laid solid. Probably half of it was laid 20 to 25 years ago, and there is no reason to condemn it. Lead-covered paper-insulated triple-concentric network laid 25 years ago is as good as, and even better than, any cable laid to-day. Vulcanized-bitumen cable can be found in the same condition, although personally I do not think that its life will be as long as that of lead-covered cable. Perhaps the link fittings shown in Figs. 6 and 7 account for the author's dislike of it. With modern shell fittings and about 60 to 70 per cent of all joints made alive, comparatively little trouble is experienced. A few years ago three-core distributors were adopted, but it was the cost of joints and not their failure that brought this about. The three-core standard cable shown in Fig. 4 was tried, but the difficulty in jointing mentioned was very serious, and I know of cases where the cores had to be cut to overcome this. The three-core cable with dummy was, I think, specially made for Glasgow to overcome this difficulty, but it is a lead-covered cable and not a vulcanized-bitumen cable. The success or otherwise of a lead-covered system rests entirely with the bonding. With three-wire network and three-wire services this means nine bonds against three with multicore cable. It is questionable whether the cost of three separate joint boxes with single-core cables and extra reinstatement, giving increased reliability, against that of one box for multicore cable, can be justified. The protection of service cables passing through walls is very important, and I agree that special precautions are necessary. The author says that the risk of fire and damage to other people's services is less with single cables than with triple-concentric or multicore cables, but my experience is decidedly the reverse. The looped neutral described in Figs. 7 and 8 might possibly be useful, but on 0·15 sq. in. and 0·25 sq. in. triple-concentric or multicore networks necessarily fused to carry full load, 75 per cent of faults are burn-outs and are not so easily bridged as suggested. I think that a strong case can be made out for triple-concentric lead-covered feeders laid solid, three-core lead-covered network laid solid in busy and heavily loaded streets, and lead-covered and armoured cable laid direct in outskirts, with three-core and twin lead-covered and armoured services laid direct, the earth test to be taken regularly, positive and negative alternately every week.

Mr. R. B. Mitchell: The question which has been raised as to the desirability of triple-concentric cables affects Glasgow very materially. As Mr. Stronach has said, there are hundreds of miles of this type of cable laid in this city. It has been used for 25 years with satisfaction, and in view of the large sizes and the congested state of the subsoil in the streets it is the only method possible. For low-tension work I do not consider ducts to be either necessary or desirable. The feeders from substations, for instance, have to take divergent routes, and in very few cases would any saving be made. The author has not mentioned the number of ducts that he would be inclined to lay in one trench. If he had a considerable number, say 12, then the question of temperature-rise on the cables laid in the centre of the nest is very serious. It may not be so bad for low-tension cable, with which the author deals exclusively, but with high-tension cables it would be a serious difficulty and I believe that in America it has already been noticed that the cables in the centre of a nest of ducts suffer very seriously from temperature increase, even with ordinary loads. On page 339 the author refers to a cable breakdown, and indicates a preference for the duct system because the cable may be most cheaply and easily repaired. Evidently he means the total breakdown of the whole length of cable, but this does not take place with present-day cable. It might have done so when insulating materials, the permanency of which was a rather doubtful quality, were used, but now a cable will break down probably at one point only and, if laid on the direct or solid system, can be repaired at that point without the rest of the cable being interfered with in any way. On page 338 the author refers to the liability of nodal points moving. We have had no experience of that in Glasgow. The load at any of the feeding points has always increased, and what had to be done to reduce the load on adjacent feeders was to lay another feeder to an intermediate point between the two feeders, so as to relieve both. When referring to the solid system, the author has always mentioned bitumen as being used as the trough filling. We have not used bitumen in Glasgow for many years, but have used instead a gasworks pitch reinforced with whin dust, which I think has proved itself equal in every respect to bitumen as a filling material and is also very much cheaper. This filling has been proved to be absolutely watertight, and also to have a very good heat-conducting capacity, which is a decided advantage with a filling material. Another very great advantage is that if ever the troughing breaks away or decays, this reinforced filling will retain its shape round the cable without the support of the trough. The author has referred to the fusing of networks. I agree that this is very desirable, but is it not also desirable to go as far as possible in that direction and isolate particular feeders on particular sections of network so that the minimum number of fuses will act on faults, or will be affected when faults occur at any one point?

Mr. R. M. Freer: I certainly agree with previous speakers regarding the looped neutral. On page 340 the author mentions the use of earthenware troughing to protect the cable from acids. I can vouch for the effectiveness of that method. We have in one particular spot a vulcanized-bitumen cable laid solid in earthenware troughing passing alongside acid boilers, where it is more the practice than otherwise to have spills. The cable has been working for 9 or 10 years and its insulation resistance is still high.

[The author's reply to this discussion will be found on page 363.]

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT LONDON, DUBLIN, BIRMINGHAM, MANCHESTER AND GLASGOW.

Mr. H. W. Taylor (*in reply*): In attempting to compare the various type of systems used in three-wire direct-current networks, it should not be forgotten that the enormous differences in local conditions make it impossible to form any definite conclusions that will be applicable to every case. The most that can be hoped for is to arrive at some conclusions of common, though by no means universal, application. Even such conclusions when obtained as the result of individual observation are necessarily coloured by the conditions prevailing on the systems where the experience has been gained. This fact is clearly discernible in the discussion. Whilst reading the paper before the various Centres, I have been greatly impressed by the conflicting opinions of engineers in different localities. We are all, perhaps, inclined to become unduly prejudiced in favour of or against a system with which we are most conversant.

A point that I should like to emphasize here is that the paper was written from the point of view of an undertaking of medium size. It is therefore a little unfortunate, though perhaps unavoidable, that most of those who have taken part in the discussion are connected with some of the largest undertakings in the country, with the result that many of their remarks are due to their experience of the exceptional conditions prevailing in very large cities. To these I would suggest that, though many of the recommendations in the paper are not applicable to their cases, they may be to the more numerous smaller undertakings.

There are one or two points that have given rise to more general adverse criticism, with which I will deal before proceeding to reply to the remarks of individual speakers.

Basis of comparison of feeders.—The choice of current-carrying capacity as a basis of comparison of feeders is disapproved because the voltage-drops on feeders of different cross-sectional areas are not the same and that these drops, on long feeders loaded up to the rating shown in Table 1, are too high. Let me first of all make it quite clear that the results shown in Table 3 are only intended to be a basis of comparison, and that "wherever they can be adopted" the sizes indicated are permissible. Local conditions will always be the deciding factors in the choice of the size of a feeder. As it is impossible to introduce this factor in attempting to form a general conclusion, the most that can be given is a comparison, based on some property common to all, that will provide a starting point from which the true value of a feeder can be assessed when local conditions compel modifications to be made.

I do not altogether subscribe to the opinion of several speakers that voltage-drop provides a better basis for this purpose than does the one I selected. Equal voltage-drops entail the use of cables of the same size, thus introducing another variable quantity that may be called the "earning capacity" of the cable, which would have to be considered together with the respective costs before a true comparison could be made. For instance, a single-core cable loaded as it would be to a lower percentage of its maximum rating is a much greater asset to a network, from the points of view of long life and reserve in case of emergency, than a triple-concentric cable of the same section will be. This latter point may be of considerable importance in a medium-size network with comparatively few feeders, where the failure of one may throw considerable additional load on another. It was to preserve this true basis that I chose to compare those sizes of cables that would, under favourable circumstances, give the same results, instead of taking the nearest standard sizes, and I stated at the time that such non-standard sizes would not of course be used in practice.

This voltage-drop basis would also make it impossible to take advantage of the higher permissible loading of the single-core cable which sometimes, in the case of short feeders, is very useful in obviating the necessity of boosting arrangements for the long ones. I am thus of the opinion that, bearing in mind its imperfections and limitations when making comparisons, current-carrying capacity forms a convenient basis.

As regards the current loadings shown in Table 1 being too high, I would point out that these are the maximum permissible loadings that the cable will stand if called upon, and it is not suggested that cables should normally be loaded up to such values. This, however, does not impair their usefulness as a basis of comparison.

Looped-neutral services.—Some little confusion seems to prevail as to the advantages of this type of service and the conditions under which it is used. The great majority of faults on a triple-concentric distributor, being due to external causes, occur between the outer and middle cores, i.e. between the neutral and one live core, and the cable has to be isolated until the fault has been repaired. For locating faults on distributors, ordinary tests are often rendered unreliable owing to the disturbing influence of the numerous service connections. The cable has then to be exposed and tested after cutting the neutral, perhaps in several places, before the fault is located. To have a convenient method immediately accessible of breaking the neutral, means that a fault can be located more quickly and with less cost, particularly when the roadway is of a type that is expensive to excavate and reinstate. It should be noted that during these operations the cable, contrary to Mr. Wigham's presumption, is quite dead, so that no harmful results would be obtained by breaking the neutral at more than one point, though it is usual to have only one such break whilst testing. Having located the fault between two looped services the neutral links are withdrawn at these points. If the distributor is fed from both ends it then becomes possible to make the inner cores alive with their own polarity, thus giving the correct supply to all the consumers with the exception of those tapped off the faulty length of neutral. Care should be taken to withdraw the main fuses of these latter few consumers to prevent the possibility of any of them having a pressure of 480 volts across their installations owing to this length of neutral being

alive, usually from the middle core. Should the fault be a short-circuit between all three cores, by making both inner cores alive from, say, the positive side at one end, the supply is again restored to the same consumers as before, but the meters of those connected to the negative side will be reversed. This will not result in a serious loss to the supply undertaking as such conditions will not usually last for any appreciable time; but if the premises supplied are mainly shops and business premises, as will generally be the case where these services are adopted, such a temporary supply may prevent considerable loss and certainly much inconvenience being caused to these consumers. This type of service is of little practical value on a lead-covered cable, its usefulness being confined to the triple-concentric vulcanized-bitumen cable laid solid, the earth leakages on which, under the above conditions, are usually small.

With regard to Mr. J. S. Highfield's suggestion of illegality, I would point out that no testing is done on consumers' premises; but, notwithstanding this, I think that in the Provisional Orders of most undertakings, authority will be found for their " . . . responsible agents to enter upon the premises of the consumers at all times, for the purpose of inspecting, repairing or testing any cables or apparatus installed therein." Quite apart from this authority, my experience is that consumers, particularly shop-keepers, are only too anxious to afford any assistance within their power in order to expedite the restoration of their supply. None of the possible consequences feared by Mr. Forrest and others, have been experienced with the many services of this type that have been laid by the undertaking with which I am connected, since this paper was first written. The depreciatory remarks of several speakers on this question are, I think, due partly to them not having quite grasped the essential details and to being unfamiliar with its working in actual practice.

Mr. Ratcliff raises many interesting points in the course of his remarks. He advocates the use of a neutral conductor for a distributor of the same size as the outer, and I can appreciate that this may be justifiable in a large city where there may be a considerable heating load which renders a reasonable balance difficult to obtain. I doubt, however, whether this policy could be proved economically sound for general practice, as the results of any tests that I have taken indicate the usual size of neutral to be sufficient. If steel tubes are adopted in the place of earthenware conduits it will be necessary to use an armoured cable where there is any roadway vibration, as the latter will quickly wear away unprotected lead sheathing.

I certainly agree with several speakers that it is necessary to bond and earth the lead sheathing of a lead-covered cable. It was perhaps because this is such a common practice that I made but incidental reference to it in the paper. With regard to armouring, I have been unable as yet to form any definite conclusion from my own experience, but I think that some method of bonding it to the lead sheathing as shown in Fig. D is beneficial, in spite of the fact that on some networks, where no attempt is made to do this, no resultant trouble is experienced.

I have never seen a testing strip (as described in the paper) applied to a low-tension network, but having found it beneficial in the case of e.h.t. cables I made reference to it, in the hope that some useful points in connection with it might arise during the discussion. I agree with Mr. Perryman that a triple-concentric distributor has to be isolated immediately under fault conditions, but this being the case a testing strip on such a cable would be of no advantage, as its suggested use was to enable a fault to be located without the cable itself having to be disconnected. I am inclined to agree with Mr. Crellin and others that the cost of such a strip on low-tension networks would render it too expensive a luxury. I am surprised that in arriving at his conclusion of the superiority of the triple-concentric cable Mr. Perryman makes no reference to the three-core cable, which really is its chief rival.

Mr. Ambrose seems somehow to have become a little confused with regard to my statement that a three-core cable is only manufactured in sizes up to 0·5 square inch.

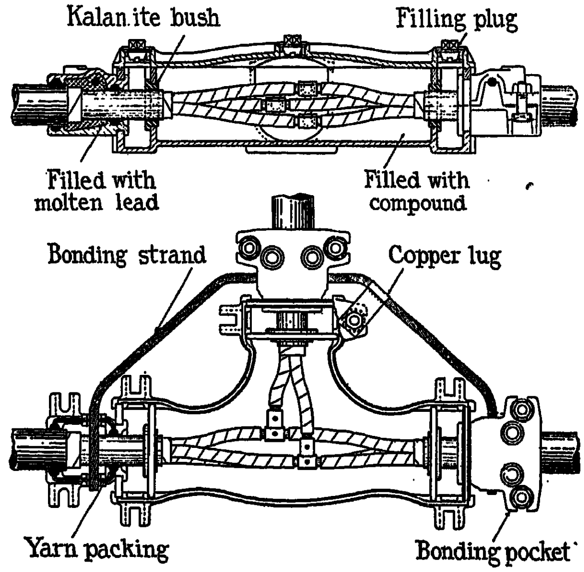

Fig. D.

This is mentioned in connection with feeder cables, not distributors, and I agree that a larger size of the latter will rarely, if ever, be required. I consider it advisable, wherever possible, to drain all manholes and network boxes, a Buchan's trap being sufficient to prevent the escape of sewer gases. I have not found a non-return valve necessary for other reasons. It is when it becomes necessary to draw a new cable into old existing ducts that very little clearance is sometimes obtained. I once had occasion to draw about two miles of e.h.t. cable with an overall diameter of 2¾ inches into an existing 3 in. duct. I have known several cases of braided cables jamming when an attempt was made to draw them out, with much more clearance than obtained in this instance.

With regard to the arrangement of the cores on a triple-concentric cable, I do not suggest that the neutral should ever be the inner, as is implied by Mr. Ambrose.

This would necessitate cutting through both live cores at both positive and negative services. On vulcanized-bitumen sheathed cables it is advisable to have the outer core the neutral, but I suggest that it would be better to have the middle core positive rather than negative, as such an arrangement would tend to keep moisture from entering the cable. It is only with lead-covered cables that, by making the outer core positive, the middle core neutral and the inner core negative the following beneficial results would ensue :—

(1) Accidental damage would be immediately apparent.
(2) Osmosis would tend to keep the cable drier.
(3) The maximum pressure between two cores would be 240 volts instead of 480 volts.
(4) A mechanically stronger outer core would be obtained, an advantage mentioned by Mr. Crellin.

I am familiar with the method of earthing the neutral described by Mr. Ambrose and referred to by Mr. Raphael, and it is the one to which I refer on page 344 in the section dealing with three-core cables. I do not, however, agree that to have a limiting resistance in the neutral earth circuit " will at any rate prevent the risk of a 480-volt shock," this being a disadvantage cited in connection with the system described in the paper which is really the same method without the resistance. Should an earth occur on, say, the negative conductor, there will be 240 volts across the resistance, and the positive conductor will be 480 volts above earth. The only effect of the resistance in allowing a leakage current to pass through the fault will be to increase the distribution losses by an amount depending on its ohmic value and, in the case of a multicore cable, to hasten the spreading of the fault to a short-circuit between cores. It does not reduce the liability of damage to consumers' installations under these conditions, and for this reason I agree with the principle of the fusing arrangements indicated by Mr. Rawll in Fig. C. It is for the same reason that I disapprove of the practice of some supply undertakings in terminating the neutral conductor of their two-wire services in a link box instead of a fuse box. A slight advantage obtained by the use of a series of fuses, the heaviest of which would correspond to the setting of the circuit breaker, is that an additional warning is given in the case of a fault which is sufficient to blow one of the lighter fuses but would not operate the circuit breaker. I recommend the use of tape-armoured cable for laying direct, as I consider that it provides better protection from the blow of a pick than does wire armouring, but the latter would appear to be more immune from the chemical action of certain types of ground.

With reference to Mr. Raphael's remarks regarding the cost of energy wasted in a feeder, I would point out that the second expression in the formula given in the paper is intended to take into account the fact that the maximum losses occur at periods of peak loads. Were this not the case no additional plant would be necessary to cope with them. As the running costs per unit at peak loads will be less than the average running costs, one would be erring on the right side by taking the latter, even if it did not represent a closer approximation to the correct figure. By reconstructing the first part of the appendix I hope that I have eliminated what may have been a slight cause for misconception.

I think that Mr. Wigham is inclined to be too favourable to the three-core distributor in his estimate of the time taken to make the service joints, as compared with that in the single-core distributor. In the first place it is only the larger consumers (whose load is sufficient to necessitate it being balanced across both sides of the system) that require a three-wire service, so that in the great majority of cases only two boxes are required for single-core cables. Furthermore, it is not correct to take the actual time to make the joints without considering the conditions under which they are made. For instance, in actual practice considerable time is saved by the jointer being able to prepare the distributor cables to suit the type of box used, whilst his men are excavating the ground, etc., preparatory to laying the service cables. The costs of laying complete services should be compared together with the time taken to carry out the whole work; this introduces the human element of the average jointer which, in my experience, enables him to return to the works at the end of the day at the same time whether he has laid a twin, concentric or single-core service. With a length of 8 yards a concentric service will cost about 10s. more than a twin cable, and the increased cost of single-core cables over twin cables will vary from 25s. to 35s., depending upon the type of boxes used.

Mr. Baker appears to be in a very comfortable position in that none of his cables are loaded up to more than one-quarter of their capacity.

Mr. Blades and others refer to the difficulty of making earthenware conduits thoroughly watertight. The following instance where this was obtained may be of interest. About two years ago a conduit line was laid through on old slag heap and it was considered advisable to take every precaution to ensure that the e.h.t. cables that were to be drawn into them would be free from the action of any acids contained in such ground. The joints of the conduits were accordingly completely surrounded with a mixture of cement and granite chippings, care being taken to see that the whole of the joint was enclosed. It was thought that the water would be more likely to take the easier path through the surrounding porous ground than to penetrate such a formidable object as protected the joints. That this reasoning was justified was shown by a recent test. A piece of clean, dry rag was pushed through two of the spare ducts and in both cases it came out only slightly "moist," in spite of the fact that the ground about the conduits was saturated by the almost continuous rainfall that had occurred from some time prior to the test. When the rags were tested they were found to be quite neutral, whilst the water contained in the ground showed unmistakably the presence of acids, which would indicate that even this trace of moisture had not come through the joints of the conduits.

I have only once had experience of trouble caused by the movement of drawn-in lead-covered cables. This was on a length of three-core 6 000-volt cable which supplied chiefly a large hand-operated electric

furnace. Practically all the wiped joints had to be re-plumbed. The trouble in this case was perhaps not so much due to expansion and contraction as to the effect of the very unbalanced load that occurred for some time after the furnace had been recharged, when there would be as much as 100 amperes out of balance, first on one core and then on another.

Mr. Blades is obviously right in assuming that the two neutral cores of a looped-neutral service are of the same size as the neutral of the distributor; the sketches shown in Figs. 6 and 7 are only intended to be diagrammatical. I do not recommend this type of service on distributors having a neutral larger than 0·1 sq. in.

I refer Mr. Allen to my previous remarks as to the reason why certain non-standard sizes of feeder cables are compared. The length of transmission possible will usually be calculated from the nodal point and will be independent of the feeder drop which his figures seem to include. I quite appreciate that single-core armoured cables would be of no use on an a.c. system, but I must remind Mr. Allen and Mr. Romero that the object of the paper is to discuss the application of various cables of a three-wire d.c. network, any advantages that some cable may have for other purposes being beyond its scope.

The case mentioned by Mr. Smith will necessitate a choice between the two evils of subsidence and corrosion. If both are equally probable I should prefer to risk the latter by laying direct a wire-armoured cable well served and compounded and surrounding it with some substance such as clay brought from another site.

The figures given in Table A by Mr. Forrest show clearly the disadvantages of single-core vulcanized-bitumen cables wherever full use can be made of the higher permissible loadings of the other types mentioned. This is substantiated by the fact that very few authorities are now laying such cables.

I do not like the example taken by Mr. Davidson of jointing a three-core cable on to a single-core distributor, as this will to a large extent nullify the advantages to be gained by having all parts of a network composed of single-core cables. The lead "tee" box seems to be the best for efficiently bonding the lead and for providing a perfectly watertight joint. It is, however, mechanically weak and requires protecting; also some method of bonding the armouring has to be devised. Fig. D shows a type of box which, whilst retaining the advantages of the cast-iron box, provides a method of bonding that is at once both simple and effective.

The seeming dislike for conduits expressed by Mr. Groves is almost as surprising as is his affection for single-core vulcanized-bitumen cables laid solid. Even assuming the rapid localization of faults possible on this type of cable under certain conditions, I should think that the substitution of lead-covered cables for the vulcanized-bitumen cables would very greatly reduce the number of faults to be localized, a fact that seems to be supported by the experience of Mr. Blades in Birmingham which enables him to speak highly of solid-laid lead-covered cables. Mr. Groves will notice that the costs of distributors shown in Table 5 are not based on current loadings and that it is not the costs but the times taken to complete alternative services which I say are the same in practice. I have already dealt with this question of costs in my reply to Mr. Wigham.

As most undertakings are favoured with a monopoly in their area of supply, I have always felt that they are, in return, morally bound to give the best possible service to their consumers. A dissatisfied consumer cannot transfer his custom elsewhere as in most other commercial transactions. It is largely the fact that I have found the single-core system to cause the least amount of public inconvenience under fault conditions that has led me to favour this type of network. Perhaps Mr. Romero is right in suggesting that I attach too much importance to the fault question, but in writing the paper, the subject matter for which has been obtained exclusively from my own experience, I may have lost sight of the fact that I have perhaps had more than my share of this trouble.

The scrapping of a vulcanized-bitumen triple-concentric distributor and its substitution by, say, a lead-covered and armoured three-core cable is a policy which I, as a mains engineer, can heartily support. Unfortunately, directors or committees are sometimes hard to convince of the necessity of expending what may be a considerable sum from which no financial benefit will be derived other than a saving in running costs. There may be many reasons for this attitude, more particularly perhaps in privately owned concerns, and it is quite conceivable that, though such a large expenditure might not be sanctioned, it would be considered justifiable to spend an extra 25s. on each of a few looped-neutral services in view of the resultant saving in the event of faults that are very liable to occur on some old vulcanized-bitumen distributors. This could hardly be classed as an "expensive" precaution. In all the calculations given in the paper of the costs of laying single-core cables, allowance has been made for the increased costs of carting, carriage on returned empties, tiles and the laying of three cables instead of one.

Mr. Lovell's suggested anchoring of a drawn-in cable at every box seems as opposed to Mr. Groves's view that flexibility is d ired at this point as is the favour he shows to wooden troughing, contrary to the views of other speakers. I am inclined to agree with Mr. Crellin that having the smaller neutral conductor as the outer of a triple-concentric cable is to be regarded rather as a mechanical weakness than an advantage. I am glad that Mr. Lovell is one of the few critics who have expressed their appreciation of the difficulty of forming conclusions in a paper dealing with a subject in which no two jobs are alike.

In response to Mr. Mallinson's suggestion I have included in the paper, information as to the prices of copper and lead at the time the various costs were calculated.

The fires that occurred on consumers' premises mentioned by Mr. Lamb when the potential of the neutral was raised were probably due to no protection against this possibility, such as that described by Mr. Rawll, having been taken. I am pleased to find that Mr. Lamb has also experienced the benefit of the use of conduits under certain busy thoroughfares, as several of the speakers in the discussion express the view that these are the very places where conduits are impossible.

Mr. Henderson and Mr. McLellan have evidently

overlooked the qualification which follows my remarks apropos the necessity of making a triple-concentric cable dead whilst jointing. That there is some inconvenience and difficulty experienced is evident from Mr. Stronach's admission that only 60 to 70 per cent of the joints can be made with the cable alive. Mr. Henderson will also notice that only in Table 3, relating to feeders, are the calculations based on current-carrying capacity, whilst those for distributors shown in Table 5 are based on voltage-drop, the sizes of cables being the same in each case. As the remark on page 346 which he quotes is in reference only to distributors, his charge of inconsistency cannot be substantiated.

Mr. Berry speaks from the viewpoint of a very large undertaking where conditions are exceptional and different from the majority of cases. Where there are very many feeders resulting in short distributors I can quite appreciate that the limiting factors will tend to be the reverse of those stated in the paper, feeders being limited by voltage-drop and distributors by current-carrying capacity.

Testing for a fault with only the neutral core of a triple-concentric cable cut instead of all three cores will undoubtedly give unreliable results if lamps or a "megger" are used for testing. If the cable is tested by closing it in through a light lead fuse of about 15 amperes' capacity, however, absolutely reliable results are obtained. Should such a test be necessary during working hours and it is doubtful whether the fuse has blown owing to load or the effects of the fault, it is not a difficult matter to open the consumer's main switches and test again. The cases when this precaution is necessary are, however, extremely rare.

By referring to my reply to Mr. Henderson, Mr. Stronach will see that his first remark is inaccurate. I can quite understand his reluctance to speak with disfavour of the triple-concentric cable, but after having questioned my right to condemn such a type for distributors, that he should proceed in his concluding remarks to do the same thing himself by advocating a three-core cable for such work is at least surprising.

Mr. Mitchell has mentioned a substitute for bitumen which has given every satisfaction. It would be interesting to know whether this compound will flow at as low a temperature as bitumen which enables the latter sometimes to seal up and so arrest an incipient fault due to the slight local heat caused by the leakage current.

Mr. Spalding is correct in his assumption as to the reason why I have allowed for a neutral cable one half the size of the outer. Where there are several feeders feeding a congested area the adoption of a size such as he indicates would no doubt be justifiable.

I have not found it easier to secure efficient bonding on a multicore than on a single-core network, nor have I experienced any trouble due to the smaller size of neutral cable used on the latter. Any danger there is of mechanical damage is certainly eliminated in the multicore cable. I have, however, known several cases where the neutral of a triple-concentric cable has been burnt clear by a fault which left two live cores continuous, thus causing considerable damage to consumers' installations. I do not quite follow the description given by Mr. Spalding of the fault in a street lamp but if, as he says, the fault is a "dead" short-circuit caused by the fusion of the outer and neutral fittings, the limiting resistance in the station neutral earth circuit would appear to have no bearing in the situation as this is concerned only with earth leakages.

It is, of course, quite incorrect to add the figures shown in Table 4 to those of Table 3 in order to arrive at the whole cost of laying a feeder inclusive of excavating, reinstating, etc. Table 3 itself gives these total costs, Table 4 merely showing the proportion of these amounts, exclusive of cable, that will have to be re-incurred should it be necessary at any future time to increase the size of the feeder.

In the little experience I have had of fibre conduits I have known of no damage being done to the lead sheathing of the cables drawn into them. Their use was, however, discontinued in favour of the earthenware conduits.

THE USE OF SINGLE-CORE ARMOURED CABLES FOR ALTERNATING CURRENTS.*

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SUMMARY.

The paper is intended to form a corollary to that of Professor Cramp and Miss Calderwood† and deals with the losses involved in the distribution of alternating currents in sheathed cables in which the sheath is of magnetic material.

Single-core rubber-insulated cables, each enclosed in a separate iron tube, and also single-core cables armoured with one or two layers of galvanized iron or steel wires, are dealt with, and experimental data are given showing the measured losses in each case.

It is shown that, while the losses due to induction in a tube are considerable, those in a wire-armoured cable are comparatively very small, and also that the distance separating the individual cables forming a circuit has very little effect in determining the losses involved. In the case of the wire-armoured cable, also, the connection of the sheaths of separate cables so as to form a closed sheath circuit has no appreciable effect upon the losses, and the current which will flow in such a circuit is so small as to produce no considerable heating.

INTRODUCTION.

The gradual increase in the voltages employed in the transmission of three-phase power has introduced serious problems in regard to the construction of three-core cables, the insulation of which is capable of withstanding the dielectric stresses involved, and for this reason the possibility of using three separate, single-core, armoured cables is of importance.

It was shown by Prof. Cramp and Miss Calderwood in their paper that in the case of a single-core cable sheathed in non-magnetic material, such as lead, the circulating currents to be expected in the sheath, and the consequent watts lost, are capable of mathematical determination. When, however, the material of the sheath is such as to affect the magnitude and distribution of the magnetic field set up between two such cables, these methods fail. The losses in single cables carried in iron pipes have also been investigated mathematically by Field,‡ but this calculation does not apply to two such cables laid side by side (whether with sheaths connected or not), and further assumes that the pipe is homogeneous over its cross-section, so that the determination cannot be applied to brazed or close-jointed tubing, nor to armoured cables.

In wiring houses also, for lighting on the conduit system from d.c. supplies, it is often convenient to convey single conductors in a tube in certain parts of the circuit. When the supply is alternating current, however, it has always been regarded as essential that every tube should contain the lead and return conductors of a circuit, as it was held that the inductive effect of a steel tube carrying a single conductor would lead to heating and excessive losses.

The research under review was undertaken for the purpose of investigating the conditions under which the use of single-core insulated cables, either enclosed in steel tubing of various types of construction or armoured with galvanized steel wires, is a practical and commercial possibility.

CONDITIONS INVESTIGATED.

Seven different sets of conditions were investigated, the description of the cables and methods of enclosure in each being as follows:

(A) 37/0·083 in. single-core, V.I.R.* cable in $1\frac{1}{4}$ in. (external diameter) heavy gauge, screwed, welded electrical conduit (see Table 1).

(B) 7/0·048 in. single-core, V.I.R. cable in $\frac{5}{8}$ in. (external diameter) heavy gauge, screwed, welded electrical conduit (see Table 2).

(C) 19/0·056 in. single-core, V.I.R. cable in $\frac{3}{4}$ in. (external diameter) light gauge, grip-connected, brazed-jointed electrical conduit (see Table 3).

(D) 7/0·048 in. single-core, V.I.R. cable in $\frac{5}{8}$ in. (external diameter) light gauge, grip-connected, closed-joint electrical conduit (see Table 4).

(E) 37/0·092 in. single-core, V.B.† cable, single armoured with 50 galvanized steel wires, each 0·08 in. diameter (see Table 5).

(F) 37/0·092 in. single-core, V.B. cable, double armoured with 107 galvanized steel wires, each 0·08 in. diameter (see Table 6).

(G) 19/0·072 in. single-core, V.B. cable, single armoured with 29 galvanized steel wires, each 0·104 in. diameter (see Table 7).

Further details of these cables are given in Table 8.

DESCRIPTION OF THE TESTS.

Fig. 1 shows the arrangement adopted for all the tests. The cable core was coupled in series with a variable resistance R and a shunt Sh, across which the current coil of a wattmeter W was connected. By means of the change-over switch S_1 a variable voltage, either from a d.c. generator or from an a.c. transformer,

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† *Journal I.E.E.*, 1923, vol. 61, p. 477.

‡ *Journal I.E.E.*, 1904, vol. 33, p 936.

* Vulcanized rubber. † Vulcanized bitumen.

TABLE 1.

Test (A). 37/0·083 *in. V.I.R.* Cable in 1¼ in. Welded Tubing.*

Main current	D.C. watts loss	$d = 0$					$d = 12$ in.					$d = 48$ in.				
		A.C. watts		Voltage-drop		Sheath current	A.C. watts		Voltage-drop		Sheath current	A.C. watts		Voltage-drop		Sheath current
		Sheath open	Sheath closed	Sheath open	Sheath closed		Sheath open	Sheath closed	Sheath open	Sheath closed		Sheath open	Sheath closed	Sheath open	Sheath closed	
amps.	watts	watts	watts	volts	volts	amps.	watts	watts	volts	volts	amps.	watts	watts	volts	volts	amps.
100	268	5 960	4 160	106·6	65	86·6	4 760	4 160	95·2	65	84·6	5 660	4 130	103·4	63·2	86
120	376	7 620	5 660	122·4	75	104·6	6 500	5 900	110	76	100·8	7 410	5 660	120	72·6	104
140	494	8 850	7 420	133·2	84·4	122·6	7 840	7 500	123·2	84·4	120·2	8 800	7 240	131·6	82·4	119
160	638	9 800	9 460	142·4	94·2	142	8 900	9 480	132·6	93·4	140	9 700	9 480	141·8	94	139
180	816	10 420	11 800	148·2	102·6	159	9 640	12 000	141	104·2	159·2	10 380	11 840	149	102	158
200	1 000	11 050	14 660	155	115	176	10 300	14 500	147·4	113	176	10 960	14 540	157	112·6	176
220	1 200	11 690	17 500	161	127	192	10 750	18 000	153	125	195	11 500	17 720	163	125	194
240	1 390	12 260	20 200	166	135	—	11 000	20 560	160	134	—	11 960	20 600	170	133	—
260	1 632	12 800	22 700	173	145	—	11 680	23 800	165	147	—	12 370	23 840	176	144	—
280	1 876	13 410	24 700	178	153	—	12 260	26 620	172	156	—	12 900	26 700	182	154	—
300	2 100	14 160	26 800	183	160	—	12 800	28 400	177	166	—	13 820	28 320	190	164	—

* Vulcanized rubber.

NOTE.—Readings adjusted to 100 yards of circuit.

TABLE 2.

Test (B). 7/0·048 *in. V.I.R. Cable in ⅝ in. Welded Tubing.*

Main current	D.C. watts loss	$d = 0$					$d = 12$ in.					$d = 48$ in.				
		A.C. watts		Voltage-drop		Sheath current	A.C. watts		Voltage-drop		Sheath current	A.C. watts		Voltage-drop		Sheath current
		Sheath open	Sheath closed	Sheath open	Sheath closed		Sheath open	Sheath closed	Sheath open	Sheath closed		Sheath open	Sheath closed	Sheath open	Sheath closed	
amps.	watts	watts	watts	volts	volts	amps.	watts	watts	volts	volts	amps.	watts	watts	volts	volts	amps.
10	59·1	205	210	28·7	26·2	5·5	252	284	33·3	25	6·5	284	284	30	21·6	6·0
15	118·5	474	500	46·2	40·8	9·0	442	442	46·6	36·6	10·0	600	442	46·6	34·1	10·0
20	192	800	867	60·3	54·1	12·75	883	662	63·3	46·6	14·0	883	691	61·6	44·1	13·75
25	296	1 221	1 050	75·7	60	14·25	1 290	1 040	76·5	55·8	18·0	1 265	1 040	75·8	54·1	18·0
30	420	1 665	1 480	87·5	69·9	17·1	1 710	1 415	88	65·8	21·25	1 800	1 450	87·5	64·1	21·8
35	567	2 080	1 955	98·4	80·6	20·5	2 205	1 900	98·3	75	25·75	2 205	1 920	98·3	73·2	25·55
40	736	2 500	2 460	108·5	90·0	22·75	2 620	2 400	108	83·3	29·5	2 620	2 460	108	82·5	29·25
45	934	2 890	2 850	115	93·0	31·5	3 155	2 970	115·5	91·7	33·5	3 155	3 060	116·6	91·6	33·5
50	1 136	3 470	3 660	122·5	101·5	35·25	3 500	3 620	123	100	37·1	3 440	3 670	122·5	100	37·25
55	1 380	3 850	4 410	128	111·5	39·2	3 850	4 290	128	110	41·0	3 790	4 380	128	109	41·0

NOTE.—Readings adjusted to 100 yards of circuit.

TABLE 3.

Test (C). 19/0·056 *in. V.I.R. Cable in* $\frac{3}{4}$ *in. Brazed Tubing.*

Main current	D.C. watts loss	d = 0					d = 12 in.					d = 48 in.				
		A.C. watts		Voltage-drop		Sheath current	A.C. watts		Voltage-drop		Sheath current	A.C. watts		Voltage-drop		Sheath current
		Sheath open	Sheath closed	Sheath open	Sheath closed		Sheath open	Sheath closed	Sheath open	Sheath closed		Sheath open	Sheath closed	Sheath open	Sheath closed	
amps.	watts	watts	watts	volts	volts	amps.	watts	watts	volts	volts	amps.	watts	watts	volts	volts	amps.
10	13·94	14·05	14·05	3·12	3·12	1·22	14·05	14·05	3·12	3·9	2·0	14·05	18·7	4·68	4·68	2·2
20	46·5	56·5	56·5	9·35	9·35	2·8	51·5	65·6	8·6	9·35	4·35	56·3	79·5	10·9	10·5	4·65
30	93·1	136	145	17·0	16·4	4·62	127	159	17·5	16·6	7·1	122	160	17·4	17·0	7·2
40	153	230	291	24·2	22·6	10·7	226	291	24·3	23·4	9·8	225	296	25·3	23·8	10·0
50	237	355	470	30·4	28·9	14·0	357	475	31·6	29·6	15·0	343	483	31·8	30·4	15·4
60	344	516	685	37·1	34·7	17·5	502	709	38·2	35·5	18·2	516	701	41·3	35·9	19·2
70	469	685	935	43·7	41·4	21·0	667	959	46	42·1	22·2	646	975	47·5	43·6	22·3
80	626	890	1 249	49·2	46·8	24·6	861	1 270	51	47·6	25·8	824	1 270	52·2	49·1	26·3
90	785	1 110	1 570	55·4	51·5	28·0	1 070	1 605	57·9	52·3	30·0	1 045	1 600	59·2	54·5	29·8
100	983	1 350	1 935	60	57	32·0	1 290	1 980	64	58·5	33·0	1 240	1 965	64·3	60	33·0

NOTE.—Readings adjusted to 100 yards of circuit.

TABLE 4.

Test (D). 7/0·048 *in. V.I.R. Cable in* $\frac{5}{8}$ *in. Light Gauge Closed-Joint Tube.*

Main current	D.C. watts loss	d = 0					d = 12 in.					d = 48 in.				
		A.C. watts		Voltage-drop		Sheath current	A.C. watts		Voltage-drop		Sheath current	A.C. watts		Voltage-drop		Sheath current
		Sheath open	Sheath closed	Sheath open	Sheath closed		Sheath open	Sheath closed	Sheath open	Sheath closed		Sheath open	Sheath closed	Sheath open	Sheath closed	
amps.	watts	watts	watts	volts	volts	amps.	watts	watts	volts	volts	amps.	watts	watts	volts	volts	amps.
10	57·7	58·3	58·3	7·27	7·27	1·3	58·3	58·3	6·86	6·86	1·5	63·1	68·0	8·1	8·1	1·75
15	106	111·5	111·5	12·1	12·1	2·2	106·8	106·8	12·1	12·1	2·4	170	126·2	10·5	10·5	2·9
20	177·5	190	197	17·3	17·15	3·25	195	202	17·6	17·3	3·5	195	219·5	18·6	18·2	3·9
25	288	331	341	23·4	23	4·5	308	321	23·4	23	4·8	324	341	23·9	24·3	5·3
30	385	456	477	28·6	28·3	5·7	465	482	29·7	29·2	6·35	463	510	30	29·5	6·65
35	516	612	661	33·9	33·1	7·0	602	666	34·4	34·3	7·6	631	681	35·6	34·8	7·9
40	662	787	840	38·4	38	8·35	778	848	39·6	39·1	8·9	801	823	41·5	39·7	9·3
45	848	973	1 067	45·3	44·5	10·5	973	1 067	46	46	10·2	1 000	1 142	45·3	44·9	12·2
50	1 050	1 195	1 310	49·3	48·9	12·0	1 180	1 340	50·9	50·9	13·3	1 240	1 409	51	51	13·8
55	1 275	1 422	1 600	53·3	53·3	13·5	1 410	1 592	54·8	54·8	15·0	1 482	1 710	55·8	55·8	15·3

NOTE.—Readings adjusted to 100 yards of circuit.

TABLE 5.

Test (E). 37/0·092 *in. V.B.* Single Wire-Armoured Cable.*

Main current	D.C. watts loss	d = 0: A.C. watts, Sheath open	d = 0: A.C. watts, Sheath closed	d = 0: Voltage-drop, Sheath open	d = 0: Voltage-drop, Sheath closed	d = 0: Sheath current	d = 12 in.: A.C. watts, Sheath open	d = 12 in.: A.C. watts, Sheath closed	d = 12 in.: Voltage-drop, Sheath open	d = 12 in.: Voltage-drop, Sheath closed	d = 12 in.: Sheath current	d = 48 in.: A.C. watts, Sheath open	d = 48 in.: A.C. watts, Sheath closed	d = 48 in.: Voltage-drop, Sheath open	d = 48 in.: Voltage-drop, Sheath closed	d = 48 in.: Sheath current
amps.	watts	watts	watts	volts	volts	amp.	watts	watts	volts	volts	amp.	watts	watts	volts	volts	amp.
100	347	352	352	7·6	7·6	0·12	352	352	5·08	5·08	0·18	352	352	5·08	7·6	0·215
120	452	596	627	7·6	7·6	0·18	520	520	10·1	10·1	0·22	503	503	12·7	12·7	0·27
140	588	917	917	10·15	10·15	0·23	810	810	14·0	12·2	0·285	753	753	15·2	16·5	0·33
160	754	1 283	1 283	14·0	12·2	0·275	1 205	1 178	16·5	17·8	0·335	1 084	1 084	20·3	20·3	0·4
180	950	1 710	1 710	16·5	16·5	0·325	1 570	1 570	20·3	20·3	0·4	1 500	1 500	25·4	25·4	0·435
200	1 190	2 170	2 170	19	19	0·37	1 981	1 981	24·1	24·1	0·455	1 895	1 895	27·9	27·9	0·51
220	1 403	2 755	2 755	21·6	21·6	0·43	2 570	2 590	27·9	27·9	0·52	2 428	2 428	31·7	31·7	0·585
240	1 625	3 360	3 325	25·4	25·4	0·475	3 070	3 070	30·5	30·5	0·58	2 890	2 890	34·3	34·3	0·65
260	1 865	3 965	3 965	27·9	27·9	0·525	3 750	3 750	33	33	0·635	3 500	3 500	38	38	0·74
280	2 120	4 650	4 650	30·5	30·5	0·57	4 260	4 280	35·5	36·8	0·7	4 050	4 050	43·1	43·1	0·805
300	2 385	5 375	5 375	33	33	0·625	4 970	4 920	40·6	39·3	0·76	4 740	4 740	45·6	45·6	0·875

* Vulcanized bitumen.

NOTE.—Readings adjusted to 100 yards of circuit.

TABLE 6.

Test (F). 37/0·092 *in. V.B. Double Wire-Armoured Cable.*

Main current	D.C. watts loss	d = 0: A.C. watts, Sheath open	d = 0: A.C. watts, Sheath closed	d = 0: Voltage-drop, Sheath open	d = 0: Voltage-drop, Sheath closed	d = 0: Sheath current	d = 12 in.: A.C. watts, Sheath open	d = 12 in.: A.C. watts, Sheath closed	d = 12 in.: Voltage-drop, Sheath open	d = 12 in.: Voltage-drop, Sheath closed	d = 12 in.: Sheath current	d = 48 in: A.C. watts, Sheath open	d = 48 in: A.C. watts, Sheath closed	d = 48 in: Voltage-drop, Sheath open	d = 48 in: Voltage-drop, Sheath closed	d = 48 in: Sheath current
amps.	watts	watts	watts	volts	volts	amp.	watts	watts	volts	volts	amp.	watts	watts	volts	volts	amp.
100	379	454	454	5·82	5·82	0·1	523	523	14·5	14·5	0·16	523	509	17·5	17·5	0·17
120	516	890	890	14·5	14·5	0·13	894	894	17·45	17·45	0·22	873	893	21·8	21·8	0·225
140	690	1 435	1 435	18·3	18·6	0·18	1 435	1 435	21·8	21·8	0·27	1 420	1 435	27·7	27·7	0·265
160	880	2 155	2 155	23·3	23·3	0·225	2 095	2 095	29·1	29·1	0·32	2 060	2 010	32	32	0·31
180	1 123	2 945	2 880	30	30	0·262	2 910	2 950	33·5	32·9	0·37	2 830	2 820	36·4	36·4	0·4
200	1 400	3 850	3 730	35	35	0·302	3 750	3 790	37·8	37·8	0·4	3 670	3 670	42·2	42·2	0·435
220	1 690	4 740	4 800	38·4	38·4	0·425	4 710	4 800	43·6	43·6	0·475	4 750	4 650	48	47·1	0·52
240	1 940	5 820	5 820	43·6	43·6	0·5	5 875	5 820	49·5	49·5	0·52	5 600	5 700	52·3	52·9	0·54
260	2 250	7 020	7 020	48	48	0·558	6 950	7 010	55·2	55·2	0·57	6 730	6 750	58·2	58·2	0·6
280	2 560	8 180	8 180	52·3	52·3	0·605	8 260	8 240	61	61	0·62	7 880	7 910	64	64	0·69
300	2 820	9 460	9 500	56·7	58·2	0·66	9 320	9 630	65·5	65·5	0·69	9 120	9 100	69·8	68·3	0·73

NOTE.—Readings adjusted to 100 yards of circuit.

TABLE 7.

Test (G). 19/0·072 *in. V.B. Single Wire-Armoured Cable.*

Main current	D.C. watts loss	d = 0					d = 12 in.					d = 48 in.				
		A.C. watts		Voltage-drop		Sheath current	A.C. watts		Voltage-drop		Sheath current	A.C. watts		Voltage-drop		Sheath current
		Sheath open	Sheath closed	Sheath open	Sheath closed		Sheath open	Sheath closed	Sheath open	Sheath closed		Sheath open	Sheath closed	Sheath open	Sheath closed	
amps.	watts	watts	watts	volts	volts	amp.	watts	watts	volts	volts	amp.	watts	watts	volts	volts	amp.
50	246	250	250	3·2	3·2	0·06	251	251	4·16	4·16	0·12	251	251	4·16	4·16	0·16
60	332	375	375	6·23	6·23	0·11	375	375	8·32	8·32	0·16	375	375	10·4	10·4	0·205
70	418	500	500	10·4	10·4	0·15	500	500	11·45	11·45	0·21	525	525	12·5	12·5	0·25
80	542	675	675	11·4	11·4	0·19	665	665	12·5	12·5	0·255	675	675	14·6	14·6	0·3
90	677	900	900	13·1	13·1	0·23	865	865	14·95	14·95	0·3	915	915	17·7	17.7	0·34
100	850	1 112	1 112	14·6	14·6	0·26	1 090	1 090	17·7	17·7	0·335	1 130	1 130	20·8	20·8	0·395
110	985	1 390	1 390	17·7	17·7	0·305	1 380	1 380	20·8	20·8	0·385	1 380	1 380	22·9	22·9	0·435
120	1 160	1 665	1 665	20·8	20·8	0·330	1 590	1 590	22·9	22·9	0·425	1 645	1 645	25·0	25·0	0·48
130	1 355	1 950	1 950	22·9	22·9	0·365	1 850	1 850	23·9	23·9	0·46	1 950	1 950	27·0	27·0	0·53
140	1 605	2 460	2 460	23·9	23·9	0·405	2 200	2 200	26·0	26·0	0·51	2 245	2 245	29·1	29·1	0·565
150	1 800	2 630	2 630	25·4	25·4	0·435	2 510	2 510	27·7	27·7	0·54	2 580	2 580	31·2	31·2	0·615

Note.—Readings adjusted to 100 yards of circuit.

TABLE 8.

Comparative Table of Results.

Test	(A)	(B)	(C)	(D)	(E)	(F)	(G)
Type of main cable	V.I.R.	V.I.R.	V.I.R.	V.I.R.	V.B.	V.B.	V.B.
Size of main cable	37/0·083 in.	7/0·048 in.	19/0·056 in.	7/0·048 in.	37/0·092 in.	37/0·092 in.	19/0·072 in.
I.E.E. rating (amperes)	184	34	70	34	214	214	97
Type of sheath	Tube	Tube	Tube	Tube	Armour	Armour	Armour
Description of sheath	Welded	Welded	Brazed	Butt	Single	Double	Single
External diameter of sheath	1·25 in.	0·625 in.	0·75 in.	0·625 in.	1·55 in.	1·77 in.	1·16 in.
Resistance of sheath per 100 yards of circuit, ohms	0·375	1·26	1·08	1·75	0·122	0·056	0·124
Permeability of sheath section	518	378	314	113	6	17	11
Sheath current for I.E.E. rating (main current), amps.	153	24·7	22·2	7·25	0·5	0·46	0·33
Ratio: Sheath current/main current	0·832	0·725	0·317	0·214	0·0023	0·0021	0·0034
Percentage increase in sheath current for $d = 12$ in. over that for $d = 0$	1·5	4·6	3·1	11	21·4	10·5	28·8
Percentage increase in sheath current for $d = 48$ in. over that for $d = 0$	1·0	4·6	3·1	13·3	40	11·1	52
Impedance per 100 yards of circuit, ohms	0·575	2·13	0·60	0·96	0·125	0·157	0·177
Dead resistance per 100 yards of circuit, ohm	0·026	0·47	0·096	0·429	0·029	0·035	0·065
Effective resistance per 100 yards of circuit, ohms	0·379	1·57	0·196	0·541	0·0505	0·093	0·109
Ratio: Impedance/dead resistance	22·2	4·53	6·25	2·24	4·3	4·5	2·73
Ratio: Effective resistance/dead resistance	14·65	3·34	2·04	1·26	1·74	2·68	1·68
Watts loss per ampere of main current per 100 yards of circuit	67·4	48·3	13·7	18·4	10·8	21·3	10·9
Voltage-drop per 100 yards of circuit, volts	106·2	73·5	42·0	32·8	26·6	42·3	17·7

could be applied to the cable, the current in which was indicated by the ammeter A_1. The potential coil of the wattmeter was connected across the ends of the cable, and the voltage across these ends, or that across the ends of the sheath (whether tubing or armour) could be read by means of the voltmeter V. The two sheaths were bonded solidly together at one end, while a switch S_2 and an ammeter A_2 were connected in series across the other ends. In this way the watts

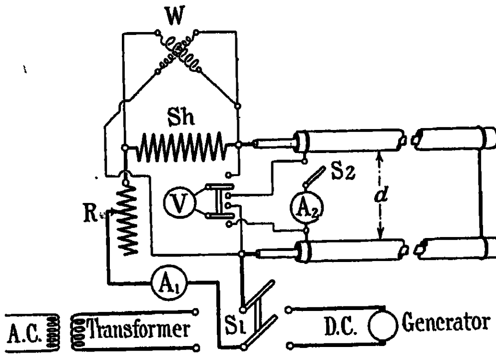


FIG. 1.—Diagram of connections for tests.

lost in the circuit, and the voltage-drop, could be read with the sheath circuit open or closed, while the current circulating in the sheaths, when these were bonded together at both ends so as to form a closed circuit, could also be read.

Owing to the short length of the cables which could be tested (up to 72 ft. of single conductor or 36 ft. of circuit) there was a large difference between the current

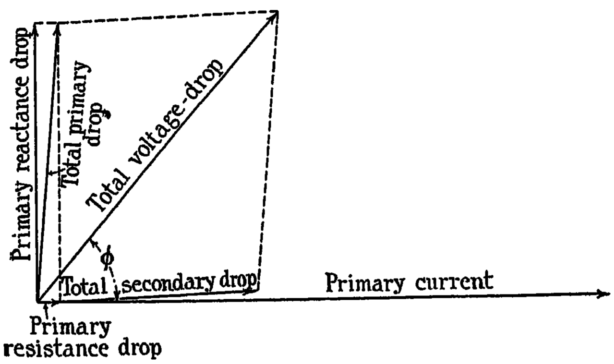


FIG. 2.—Vector diagram.

in the conductors and the potential difference between them. This necessitated the use of the shunt Sh and very careful calibration of the instruments against a Drysdale potentiometer on both direct and alternating currents.

In order to avoid possible errors due to adjacent magnetic material, etc., the wattmeter was placed in a separate room some yards from the cables under test, and the connecting leads to the current and potential coils of the instrument were of twisted flexible. A test at varying frequencies showed that the error due to self-induction was negligible.

Each test comprised three sets of readings, one set for each value of d (the distance separating the cable sheaths), viz. $d = 0$, $d = 12$ in., and $d = 48$ in.

Each set of readings included the following observations for each value of the main current :—

(1) Watts lost with direct current in the main conductors.

(2) Watts lost with alternating current in the main conductors
  (a) with the sheath circuit open, and
  (b) with the sheath circuit closed.

(3) Potential difference between the ends of the cable
  (a) with the sheath circuit open, and
  (b) with the sheath circuit closed.

(4) Current in the sheath circuit with this circuit closed.

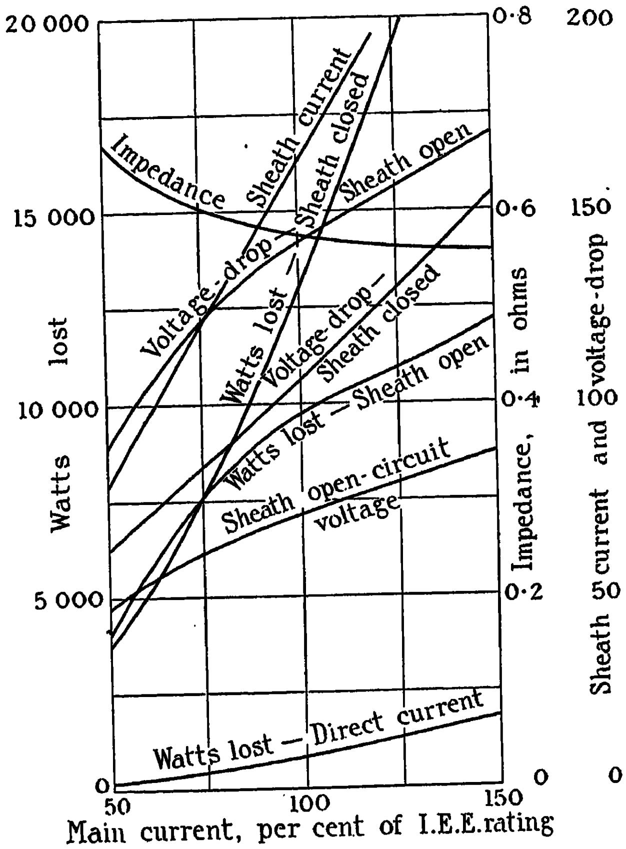


FIG. 3.—Test (A).

The frequency of the alternating supply throughout the tests was 50 periods per second.

Observations were also made of the voltage across the ends of the sheath circuit with this circuit open and with the sheaths 12 in. apart.

The main currents employed during each test were approximately those corresponding to a range of 50 to 150 per cent of the I.E.E. rating of the cable under test, with an upper limit of 300 amperes.

The readings taken under each set of conditions are set out in Tables 1 to 7, the values of watts lost and voltage-drop being adjusted to a length of circuit of 100 yards, or 200 yards of single conductor.

Table 8 shows, for purposes of comparison, the principal readings under each set of conditions corresponding to a current in the main conductor equal to the I.E.E. rating, and for sheaths 12 in. apart.

The readings given in Tables 1 and 5 are plotted in Figs. 3 and 4 against the current in the main cable as a percentage of the I.E.E. rating. These curves apply only to circuits in which $d = 12$ in.

Tests were also made upon samples, about 3 in. long, cut from the tubes and armoured cables, to determine

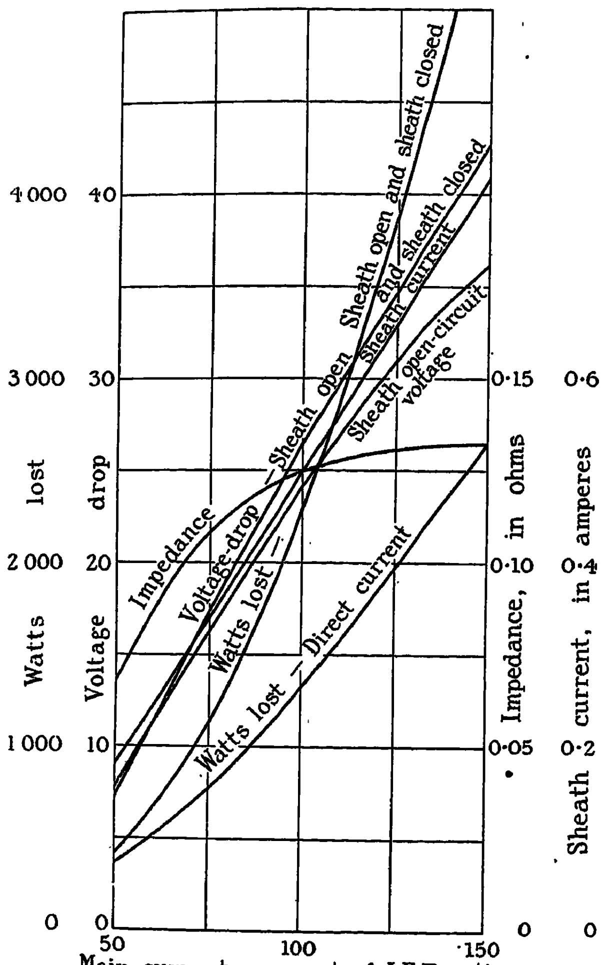


FIG. 4.—Test (E).

the permeability of the circumferential magnetic path in the sheath. In the case of the armoured cables, the permeability given in the table is that of the zone including the armouring and of width equal to the diameter of one armour wire. Primary and secondary coils were wound longitudinally upon the specimens, and the measurements of flux were obtained, by means of a ballistic galvanometer, for various values of H. In the case of the armoured cables, the copper conductors and a portion of the insulation were carefully removed from the specimens, so as to avoid disturbing the relative positions of the armouring wires. The permeability curves derived from these tests are plotted in Fig. 5.

In Fig. 6 the watts lost per ampere of main current per 100 yards of circuit are plotted, for each of the seven tests, against the main current as a percentage of the I.E.E. rating.

REVIEW OF THE RESULTS OBTAINED.

The outstanding facts to be derived from a study of the tables and curves are as follows:

Watts lost.—In the case of test (A) the loss is enormous, and on a 500-volt circuit would amount to 13·5 per cent of the power input for every 100 yards of circuit. In test (B) this figure is reduced to 9·7 per cent, in test (C) to 2·74 per cent and in test (D) to 3·68 per cent.

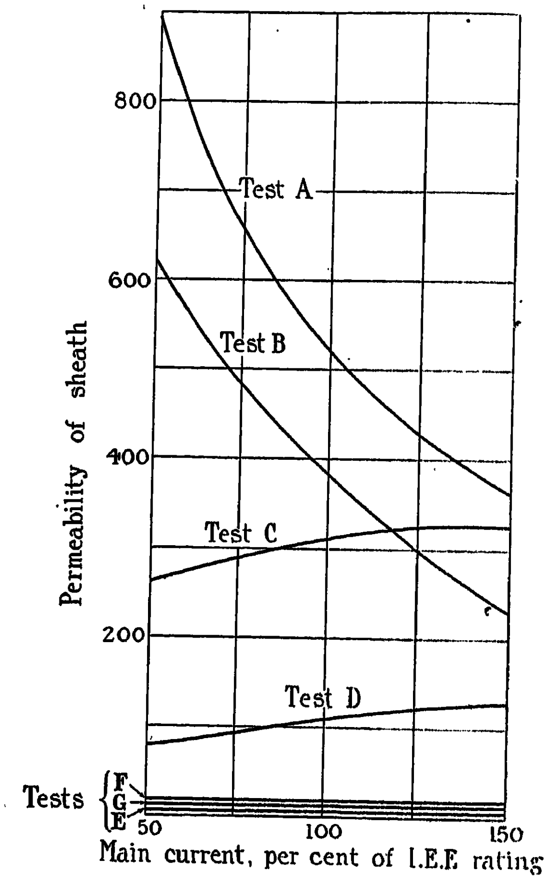


FIG. 5.

For the single-armoured cables [tests (E) and (G)] the loss is 2·16 per cent and for the double-armoured cable [test (F)] 4·27 per cent. The corresponding figures for watts lost due to dead resistance are: (A), 0·9 per cent; (B), 3·25 per cent; (C), 1·34 per cent; (D), 1·47 per cent; (E), 1·19 per cent; (F), 1·19 per cent; (G), 1·7 per cent.

The losses in the armoured cables appear high in comparison with the sheath currents, but, as will be explained later, this is largely due to the spiral lay of the armouring wires, and the loss is a "sheath loss" rather than a "sheath circuit loss." As defined in the

paper by Prof. Cramp and Miss Calderwood, " sheath loss " is the loss due to eddy currents confined to the sheath of one cable, while " sheath circuit loss " is due to eddy currents in the closed circuit formed by the sheaths of two cables when these sheaths are bonded together at each end. It will be noticed from Fig. 4 that the curves of watts lost with sheath open and with sheath closed coincide.

The watts lost in tests (A) and (B) are quite sufficient

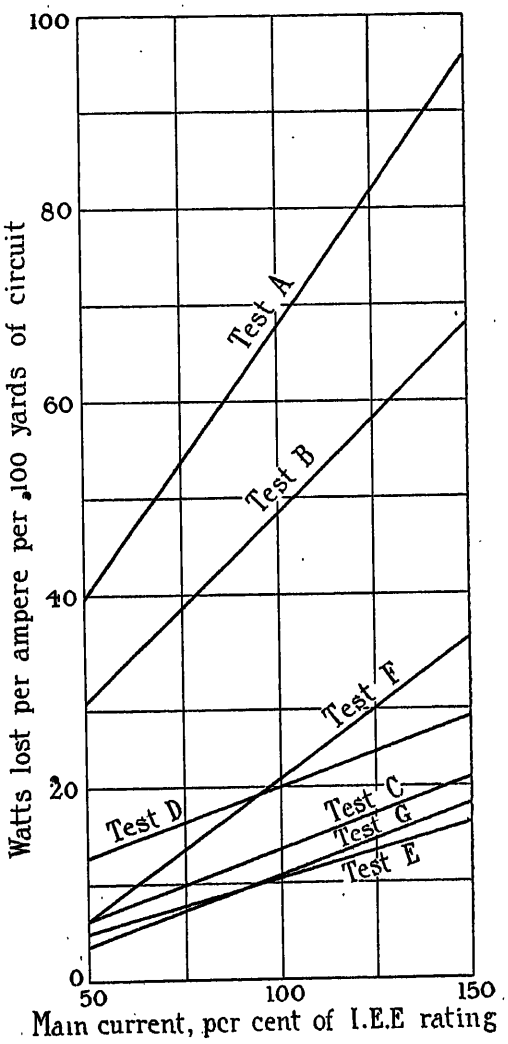


Fig. 6.

to cause serious heating of the tubing. In the other tests, however, the heating was too slight to be of serious importance and in the case of the armoured cables it was imperceptible.

From the point of view of practical working efficiency, therefore, it would appear that the use of any type of enclosure of a magnetic nature, except brazed tubing of light gauge, or single armouring, is impracticable, while even in these two types the losses will be approximately double those due to the dead resistance of the cables.

It will be noticed that the watts lost with the sheath circuit closed—the usual condition obtaining in practice—varies inappreciably with the value of d in cases (A), (B), (C), (D) and (F). In case (E), however, the value for $d = 12$ in. is 91 per cent, and for $d = 48$ in., 87·5 per cent of that for $d = 0$.

Sheath current.—The ratios of sheath current to main current given in Table 8 show a very marked difference between the tubing and the armoured cables. In test (A) the sheath current was but little less than the main current, and the tubing became unbearably hot to the hand. In tests (E), (F) and (G) the maximum current in the sheath, with a current flowing in the main conductor equal to 150 per cent of the I.E.E. rating, was less than 1 ampere.

The variation in sheath current with spacing of the sheaths was most marked in test (E), and was comparatively slight in all the other tests.

Voltage-drop.—The impedance of the system in tests (B), (C), (D), (E) and (F) varied between 2·24 and 6·25 times the dead resistance. In test (A) it was 22·2 times the dead resistance. In any case, a loss of 26·6 volts per 100 yards of circuit, or over 6 times the normal allowance for cables carrying direct current, is a very serious disadvantage.

The drop in voltage increases with increasing separation of the sheaths, the variation being slight, except in the armoured cables. In test (E) the increase from $d = 0$ to $d = 12$ in. was 30 per cent, and from $d = 0$ to $d = 48$ in., 39 per cent. In test (F) the increases were 11·4 per cent and 12·3 per cent respectively, and in test (G), 28·8 per cent and 52 per cent.

Theoretical Survey of the Experimental Results.

The lead and return conductors themselves, and the circuit formed by the magnetic sheaths enclosing them, may be regarded as forming the primary and secondary windings of a current transformer, each winding consisting of one turn.

Since the primary is situated within the sheath, there will be a certain amount of primary leakage reactance due to the flux within the inner circumference of the sheath, but the whole of the counter-flux set up by the current induced in the secondary must thread the primary circuit, so that there can be little secondary leakage reactance, and practically the whole of the secondary losses must be due to eddy currents and, to a small extent, to hysteresis.

This being so, the primary leakage reactance corresponding to any primary current can be calculated by deducting from the total reactance (obtained from the primary applied voltage with secondary on open-circuit) the mutual reactance obtained from the secondary open-circuit voltage under the same conditions.

Knowing this primary reactance, we are able to construct the vector diagram of the transformer under short-circuit conditions, i.e. with the sheath circuit closed (see Fig. 2).

Considering the case illustrated in Fig. 7, which represents the conditions of test (A) when the sheath circuit is open, the direction of the eddy currents in the sheath enclosing conductor " a," and due to the flux in the sheath only, will be as shown in the small

elements "a_1," "a_2," namely, away from the observer in "a_2" and towards the observer in "a_1."

Now consider conductor "a" with its magnetic sheath alone. If we assume that the resistance of the longitudinal paths of the currents in "a_1" and "a_2" is negligible, we shall have these currents concentrated in the inner and outer layers respectively of the sheath, and each equal in magnitude to the current in the main conductor "a."

Introducing now the second conductor "b" and its sheath, a portion of the flux due to the current in "b" will cut the sheath of "a" and will disturb the distribution of these currents. For non-magnetic sheaths, Prof. Cramp and Miss Calderwood have shown that the influence of this second field is of importance. In the case under consideration, however, the ratio of the flux in the iron of sheath "a," due to conductor "a," to that set up by conductor "b" is so great that the effect is negligible.

This conclusion is borne out by the experimental results, since the increase in sheath current for increasing distances d separating the sheaths is only 1 per cent in test (A); in test (E), when the permeability and sectional area of the iron path is greatly reduced, it reaches 40 per cent (see Table 8).

The relative magnitude of the flux in the sheath to that between the sheaths, is given approximately by :—

$$\frac{\Phi_1}{\Phi_2} = \frac{0\cdot 2I \log_e (r_1/r_2)\mu l}{2\{0\cdot 2I \log_e (d + r_1)/r_1\}l}$$

$$= \frac{\log_{10} (r_1/r_2)\mu}{2 \log_{10} (d + r_1)/r_1}$$

where Φ_1 = flux in sheath,
Φ_2 = flux between sheaths,
d = distance between sheaths,
r_1 = external radius of sheath,
r_2 = internal radius of sheath,
I = current in main conductor, and
l = length of one sheath, adjusted to 100 yards of circuit.

In the case of test (A), for $I = 184$ amperes and $d = 30\cdot 4$ cm, we have

$r_1 = 1\cdot 58$ cm, $r_2 = 1\cdot 375$ cm, $l = 9\,130$ cm, $\mu = 392$,

so that

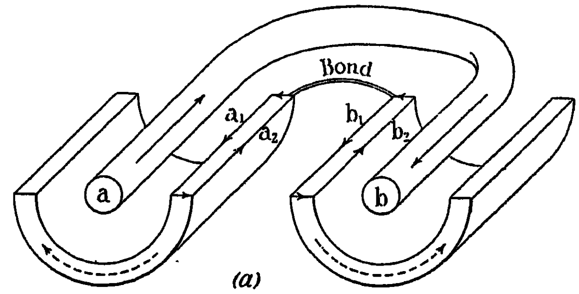
$$\Phi_1 = 0\cdot 2 \times 184 \times \log_e (1\cdot 58/1\cdot 375) \times 392 \times 9\,130$$
$$= 18\,570\,000$$
$$\Phi_2 = 2\{0\cdot 2 \times 184 \times \log_e (31\cdot 98/1\cdot 58)\} \times 9\,130$$
$$= 2\,012\,000$$
$$\frac{\Phi_1}{\Phi_2} = \frac{18\cdot 57 \times 10^6}{2\cdot 012 \times 10^6} \doteq 9\cdot 23$$

and the open-circuit voltages due to the two fluxes will be

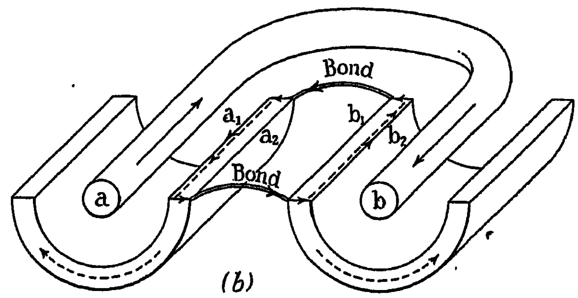
$$E_1 = \frac{2\pi \times 50 \times 18\cdot 57 \times 10^6}{10^8}$$
$$= 58\cdot 3 \text{ volts per 100 yards of circuit.}$$
$$E_2 = E_1 \times \frac{\Phi_2}{\Phi_1}$$
$$= 6\cdot 3 \text{ volts per 100 yards of circuit.}$$

Fig. 7 (*a*) represents diagrammatically a longitudinal section through the sheaths, the conditions being those described in the tests as "sheath circuit open." The arrows indicate the direction of flow of the sheath eddy currents, due to the flux in the sheath, under these conditions, the assumption being that the current will be more or less concentrated in the inner and outer circumferences of the sheaths, represented by the elements a_1, a_2, b_1, b_2.

If these were separate conductors forming inner and outer thin sheaths and separated by a middle layer of magnetic but insulating material, we could readily calculate the voltages which would be indicated by a voltmeter connected across the unbonded ends. The P.D. across the near ends of "a_1" and "b_2," for



(*a*)
Sheath circuit open



(*b*)
Sheath circuit closed

FIG. 7.—Distribution of sheath currents.

example, would be that due to the flux in sheath "b," while the P.D. between "a_2" and "b_1" would be due solely to the flux between the sheaths.

Since the whole sheath is homogeneous, however, and has a low transverse resistance, the connections of the voltmeter must be regarded as being made to every point in the sheath, both internal and external.

Under these conditions, the actual value of this "open circuit" E.M.F. may be calculated by the method given in Field's paper referred to earlier in the present paper. Field's calculations, however, assume a constant value of the permeability throughout the section of the sheath, although Thomson has shown* that the flux density and therefore the permeability vary over the section. It is necessary, therefore, to base the calculation upon the mean value of μ.

Taking the case of the large welded tube [test (A)],

* *Electrician*, 1892, vol. 28, p. 599.

the values of the terms in Field's formula are as follows :—

Resistance of total length of tube (including joints) $= 0 \cdot 0238$ ohm.
Area of section $= 1 \cdot 8$ cm^2.
$\rho = 18 \cdot 6$ microhms per cm cube.
Maximum value of current $= \sqrt{2} \times 184 = 260 = \Gamma_i$.
Frequency $= 50 = f$.
Mean value of permeability $= 518 = \mu$.
$m_i = 0 \cdot 000199 \sqrt{(\mu f / \rho)} = 7 \cdot 1$.
Mean circumference of pipe, $L = 9 \cdot 26$ cm.

$$\frac{\Gamma_i m_i}{L} = \frac{260 \times 7 \cdot 1}{9 \cdot 26} = 200$$

Thickness of pipe $= 0 \cdot 207$ cm $= h$.
$m_i h = 1 \cdot 47$.

$$P_i = \frac{\Gamma_i m_i}{l} \sqrt{\left[\frac{\cosh m_i h - \sinh m_i h}{\cosh m_i h + \cos m_i h}\right]}$$

$$= 200 \sqrt{\left[\frac{2 \cdot 29 - 2 \cdot 06}{2 \cdot 29 - 0 \cdot 1}\right]} = 64 \cdot 8$$

$$\frac{V}{\rho} = 64 \cdot 8 \{\sin \theta - \epsilon^{m_i h} \sin (\theta + 1 \cdot 47)\}$$

$$= 64 \cdot 8 \{\sin \theta - 4 \cdot 35 \sin (\theta + 1 \cdot 47)\}$$

$$\text{Mean square of } \frac{V}{\rho} = \frac{1}{\pi} \int_0^\pi \left(\frac{V}{\rho}\right)^2$$

$$= 2\,100 + 39\,500 - 18\,260\,(-0 \cdot 1)$$
$$= 43\,426$$

Root-mean-square of $V/\rho = 208$

$$V = \frac{208 \times 18 \cdot 6}{10^6} = 386 \times 10^{-5} \text{ per cm}$$

Total $V = 9\,130 \times 2 \times 386 + 10^{-5} = 70 \cdot 3$ volts.

This calculated figure agrees fairly closely with the observed value of 72 volts (see Fig. 3). The discrepancy is probably accounted for by the inclusion of the resistance of the joints giving a false value to the specific resistance.

Fig. 7 (*b*) shows the conditions when the sheath circuit has been completed by a bond of low resistance at each end. The currents in "a_2" and "b_1" now practically disappear and the current in the larger circuit embraced by "a_1" and "b_2" will be limited only by the resistance of the sheath circuit. Further, this current, instead of being a maximum at the inner and outer surfaces and falling to zero at the centre of the thickness of the sheath, is now a maximum in "a_1" and "b_2" and falls to zero at the outer surfaces ("a_2" and "b_1"), thus reducing the resistance of the sheath circuit. The open-circuit E.M.F. should therefore be greater than the E.M.F. with closed sheath circuit, and this is found to be the case, the observed open-circuit sheath voltage being in every case slightly higher than the value of the sheath voltage on closed circuit, obtained from the vector diagrams.

This redistribution of the eddy currents by the bonding together of the sheaths might be expected to cause very little difference in the watts lost between open and closed sheath circuit conditions, and this also is shown by the tests to be the case, as pointed out on page 375 when comparing the observed losses. As the sheath becomes thinner the reduction in its resistance to the sheath current on closed circuit becomes relatively less and the curves of watts lost for open and closed sheath circuits more nearly coincide.

For the armoured cables, the loss with sheath open is more marked and the loss with sheath closed is less marked, owing to the spiral "lay" of the armouring wires, different portions of the same wire being alternately internal and external to the field.

A peculiar feature of the curves of watts lost is that in tests (A) and (B) the loss with sheath open has actually a higher value than the loss with sheath closed, over the lower portions of the curves. This is most marked in test (B).

The effect is probably due to variations in the resistance of the eddy-current paths in the sheaths, the reactance of which is low, and in the distribution of these eddy currents over the sheath section. For low values of the main current the value of the flux in the sheath is relatively high, and the concentration of the eddy currents in the edges of the section, i.e. in the inner and outer layers of the sheath, will produce a high resistance and a large loss, since the sheath current is relatively constant, whereas, with sheath circuit closed, the path of the sheath currents will be of lower resistance.

Now the permeability of the sheath, as seen from Fig. 5, falls with increasing main current. As the permeability is reduced, the concentration of the sheath eddy currents in the outer layers of the sheath will be less pronounced, and the resistance of the path of these currents, and therefore the loss due to them, will increase at a lower rate than would be the case if the permeability remained constant. The sheath circuit current, however, flows in a circuit of more or less constant resistance, and the loss due to it follows approximately a square law.

It has been assumed throughout that the conductor is placed at the centre of the enclosing sheath, so that the flux in the latter is uniform over its circumference. In practice it is probable that the insulation of a conductor placed in a tube will be in contact with the sheath at a number of different points, and the flux in the sheath at these points will consequently be distorted. The extreme case would be one in which the sheath is so large compared with the conductor that the latter lies at the lowest point of the inner circumference of the sheath throughout its length.

In the cases under review, however, it is probable that the distortion produced in this way would take place at various points around the inner circumference, as well as longitudinally, and that the sum of these effects would produce little total difference in the general distribution of flux. In the armoured cables, of course, the conductor is fixed at the centre of the sheath.

The comparison on page 367 of the losses in sheathed cables carrying alternating current with those in the same cables when conveying direct current, is not altogether a just one. The difference between the curves of "watts loss—sheath circuit closed" and "watts loss—direct current" in the tables must, in

tests (A), (E) and (F) at any rate, contain, in addition to the loss due to sheath circuit current, a certain amount of additional copper loss due to skin effect. A comparison between sheathed and unsheathed cables, in both cases carrying alternating current, would therefore be more favourable to the former.

Conclusions.

From a survey of the results obtained from the tests, and of the factors contributing to those results, it is possible to derive the following conclusions:—

(1) The enclosure of a single conductor carrying alternating current at normal periodicities in a sheath of iron or steel for protective purposes need not necessarily involve excessive losses, nor produce excessive heating of the sheath.

(2) The higher the permeability of the sheath in a circumferential direction, and the greater the radial thickness of the sheath, the greater will be the losses and heating produced. Standard "heavy gauge" welded tubing is unsuitable, but the losses incurred by employing light gauge tubing, the seam of which is either brazed or merely closed, are of more reasonable magnitude. If the sheath is in the form of an armouring of galvanized steel wires, either single or double, the loss is still further reduced.

(3) It should be possible to construct a cable in which the permeability of the sheath is reduced to a negligible value by laying wires of non-magnetic material, such as aluminium, alternately with the steel wires, or by some similar means. In this case the additional loss due to the armouring will also be negligible, but the lead and return conductors must then be laid close together, as the conditions approximate to those of lead-sheathed cables, and the losses will be greater with increased separation. For the types of cable and sheath dealt with in the tests, the effect of increasing separation, up to reasonable distances, may be neglected.

(4) The loss in cables enclosed in light gauge, brazed or closed-joint tubing is but slightly greater when the sheath circuit is closed than when the circuit is open. In other words, the usual practice of securing the ends of the tubing to the metallic casing of switches, fuse-boards, motor terminal boxes, etc., will not sensibly increase the loss. In the case of armoured cables there is practically no increase from this cause.

THE USE OF SINGLE-CORE LEAD-COVERED AND ARMOURED CABLES FOR ALTERNATING CURRENTS.*

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SUMMARY.

In a previous paper Miss Calderwood and the present author examined the losses in the lead sheath of a single-core cable when carrying an alternating current, and concluded that, provided the outgoing and return cables were laid within a certain limiting distance of one another, no difficulty would arise due to eddy currents in the sheaths at normal frequencies. In the present paper this work is extended to cover the case of single-core cables that are both lead-covered and armoured.

A theoretical investigation of the reactances and losses is carried out and is checked against the actual test figures obtained by Harvey and Busby. It is shown :—

1. That the flux in the armour, the reactance due to that flux, and the appropriate hysteresis and eddy losses can all be approximately predetermined.

2. That for low-tension transmission, lead-covered and armoured cables are impracticable with armouring as at present constructed.

3. That the use of such cables for e.h.t. transmission is not precluded by the magnetic conditions introduced by the armour, and consequently such cables are practicable. There would, however, be some difficulties to be overcome due to large capacity currents when the transmission distance is great.

In the joint paper with Miss Calderwood† the losses in lead-covered cables were examined, certain rules for their use were suggested and experiments upon armoured cables were foreshadowed. These experiments have been completed by Harvey and Busby,‡ and from them the limitations of armoured cables and of cables in tubes have been deduced in the preceding paper. There remains the most important case of cables which are both lead-sheathed and armoured.

1. CORRECTION TO PREVIOUS FORMULÆ.

In approaching this problem, approximations adopted in the first paper must be borne in mind. On pages 480 and 484 of the joint paper, attention was directed to these approximations, and it was pointed out that the effect of the reaction of the circuit eddies upon the exciting field would be a reduction in the eddy losses, which, however, would not affect the general conclusions. If we regard the core and its lead sheath as the primary and secondary of a 1 : 1 ratio current transformer, then the ratio of the R.M.S. currents in the sheath and core is given by the relationship

$$\frac{I_2}{I} = \frac{2\pi f M}{\sqrt{[(2\pi f L)^2 + R^2]}} \quad . \quad . \quad . \quad . \quad (1)$$

where M is the coefficient of mutual induction between the core and the sheath, L is Maxwell's coefficient of self-induction for the sheath circuit and R is the resistance of that circuit.

In the case of a lead sheath M and L are almost equal, so that the mean loss of power in watts per cm² of mean sheath surface becomes

$$P_1 = \frac{I^2}{4\pi r} \cdot \frac{(2\pi f M)^2 R}{(2\pi f L)^2 + R^2} \quad . \quad . \quad . \quad (2)$$

where I is the current in amperes in the core, r is the mean radius of the sheath in cm, and M, L and R refer to 1 cm run of the circuit, the two former being in henrys, the latter in ohms. Throughout this paper, the expressions "cm run" or "length of circuit" mean the same measure. Thus the phrase "per 100 yards of circuit" refers to a circuit consisting of outgoing and return leads each 100 yards long.

Substituting the values

$$M = L = \frac{9 \cdot 212}{10^9} \log_{10} \frac{1 - K}{K}$$

$$R = \frac{\rho}{\pi r S} = \frac{20 \cdot 8}{10^6 r S \pi}$$

where K, ρ and S have the same meaning as in the paper cited, and taking $f = 50$, we find :—

$$P_1 = \frac{\frac{4 \cdot 4 I^2}{r^2 S}\left(\log_{10} \frac{1 - K}{K}\right)^2 \times 10^{-6}}{8 \cdot 38\left(\log_{10} \frac{1 - K}{K}\right)^2 + \frac{43 \cdot 82}{r^2 S^2}} \text{ watts per cm}^2 . \quad (3)$$

If the first term in the denominator be neglected, this reduces to $P = S I^2\left(\log_{10} \frac{1 - K}{K}\right)^2 \times 10^{-7}$ nearly, as on page 481 of the joint paper, where, however, the symbol ρ has been inadvertently printed for P.

The correction introduced by Equation (3) is not important for the case of lead sheaths, as is proved by the following table, which refers to standard low-tension paper-insulated lead-covered cable having a nominal core area of 1 sq. in. and carrying the maximum current of 932 amperes allowed by the I.E.E. Wiring Regulations.

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† *Journal I.E.E.*, 1923, vol. 61, p. 477.

‡ See page 368.

TABLE 1.

K	P	P_1	P/Q	P_1/Q	distance, l
			per cent	per cent	in.
0·01	0·0966	0·0769	537	427	83·4
0·1	0·0220	0·0210	123	116	8·34
0·2	0·0088	0·0865	49	48	4·17
0·3	0·0033	0·0033	18	18	2·78
0·4	0·00075	0·00075	4·2	4·2	2·08

NOTE.—l = distance from centre to centre of the cables.
Q = loss in the copper per cm² of mean sheath surface.

It will be noticed that the magnitude of the change is only of importance when the sheath circuit loss is quite inadmissible. In this connection the effect of frequency is of importance and might with advantage have been emphasized before. The sheath losses are proportional to the square of the frequency, so that where f is below 50, the safe distances given in conclusion No. (7) on page 483 of the original paper might well be increased.

2. APPLICATION TO ARMOURED CABLES.

This short analysis, together with the permeances and losses measured by Harvey and Busby, enables us at once to deal with cables that are both lead-covered and armoured. For the effect of the armouring is to add a new term to the values of M and L, which is usually large compared with that due to air alone; in consequence these coefficients become almost independent of the spacing of the cables, a result which was proved conclusively in the experiments.

As an example, take the case of a standard 0·5 sq. in. low-tension paper-insulated cable with the usual bedding (0·1 in. thick), and single-wire armoured with galvanized wire 0·104 inch in diameter. Then when two such cables placed parallel to one another with centres 2 in. apart are used for a single-phase circuit, power will be lost in the copper, in the lead and in the armour respectively. The sheath eddy losses in the lead are not increased by the presence of the armour and these remain negligible, although the armour eddy losses do not. When, however, the sheath circuit is closed as well as that of the armour, the values of M and L change and the sheath circuit eddy current rises. The dimensions of the cable are as follows:—

Diameter over conductor	..	0·927 in. (2·355 cm)
Diameter over lead	..	1·307 in. (3·319 cm)
Diameter over armour	..	1·715 in. (4·355 cm)
Mean radius of lead	..	0·6085 in. (1·545 cm)
Pitch radius of armour	..	0·8055 in. (2·046 cm)

To admit of direct comparison with the values in the first paper, the losses will be calculated per cm² of mean lead sheath surface, both armour and lead being assumed to be bonded at both ends.

Then when the cables are unarmoured,

$$M = \frac{9\cdot212}{10^9}\log_{10}\frac{1-K}{K} = \frac{3\cdot39}{10^9} \text{ per cm run}$$

and the power lost due to circuit eddy currents in the lead at 50 periods and with full I.E.E. current (540 amperes) in the cable is

$$P = 0\cdot0009 \text{ watt}$$

Considering now the flux in the armour, Harvey and Busby found in test G for $H = 16\cdot1$ the circumferential flux per cm axial length was 28·5, and moreover that the circumferential permeance was nearly constant. In the present instance $H = 0\cdot2 \times 540/2\cdot046 = 52\cdot78$, so that $M = 3\cdot46 \times 10^{-9}$ per cm run for the armour alone. Since the current in the armour is very small, we may add to this the increase in M due to the flux in the space between the cables, and M becomes $4\cdot61 \times 10^{-9}$. The circuit eddy loss in the lead is therefore increased from 0·0009 to 0·00166, i.e. by about 85 per cent; and the ratio of this to the copper loss at full load is as 1 : 10. So far there is nothing serious, but in addition there is the loss in the armour, which must be deduced from an analysis of the tests.

3. ANALYSIS OF THE LOSSES IN TUBES CONTAINING CABLES.

Taking first the case of the cables in tubes, we remark that there is no cause for, nor evidence of, a field in the tube other than that concentric with the cable. Also, the tube being reasonably homogeneous, the eddy currents as shown in Harvey's Fig. 7 represent the condition in the tube sufficiently closely, as is indeed proved by the agreement between the calculated and measured values of the open-circuit P.D. With the analogy of the current transformer in our minds, it is clear that, on closing the tube circuit, the difference between the measured values of d.c. and a.c. watts for a given current should be the sum of the eddy and hysteresis losses in the tube. Now the eddy losses should be (very nearly) the product of the sheath open-circuit voltage and the sheath circulating current, and the hysteresis loss can be calculated from the Steinmetz formula if a hysteresis coefficient is assumed. Thus in the case of 200 yards of tube A when the cable is carrying 184 amperes, the d.c. watts are 850, and the a.c. watts with sheath circuit closed are 13 000; so that the difference is 12 150. The open-circuit sheath voltage is 71·5 and the circulating current is 165 amperes, equivalent to 11 800 watts. Harvey's calculated mean magnetic density in the tube is 2 924 maxwells per cm². Therefore the hysteresis loss is approximately W_h = volume of 200 yards of tube × $2\,924^{1\cdot6}$ × 50

TABLE 2.

Test	Open-circuit voltage, V	Circulating current, I	Product, VI	A.C. watts – D.C. watts
	volts	amps.	watts	watts
A	71·5	165	11 800	12 150
B	38·5	24·8	955	1 260
C	21·5	22	473	510
D	27	7·3	197	145

$\times h \times 10^{-7}$ watts, at a frequency of 50, where h is the hysteresis coefficient. Taking the latter at the probable value 0·004, we have $W_h = 236$; and this added to 11 800 gives 12 036, as against the measured value 12 150. This agreement is as good as can be expected, and leads to the general conclusion that in the case of tubes the hysteresis loss is small compared with the eddy loss. Table 2 proves that contention for all the tubes.

4. Analysis of the Losses in the Armour of Cables.

The case of armoured cables is very different, as Table 3 will demonstrate.

Table 3.

Test	Open-circuit voltage, V	Circulating current, I	Product, VI	A.C. watts—D.C. watts
	volts	amps.	watts	watts
E	24	0·5	12	1 000
F	19·7	0·46	9	2 970
G	9·5	0·32	3	220

Obviously for an explanation of the loss in the armoured cables we must look further than the eddy component. If we take a ring of the armour 1 cm long, and compare the measured circumferential flux per ampere of current in the cable with that which would exist if the iron were removed, we get an idea of the apparent circumferential permeability of the armour. The tests of Harvey and Busby show that this is about 11. We know that the permeability of the wire itself must be far greater than this, however, so that while the circumferential flux is but small the flux *along* each armouring wire must be far greater. We may arrive at its value as follows :—

If l be the " lay " of the armouring and r its pitch radius, then the current I is surrounded once by a length of wire $l_1 = \sqrt{[(2\pi r)^2 + l^2]}$. If also μ be the permeability of the wire and r_1 its radius, and if the flux through the wire be uniformly distributed, then the flux along each wire

$$\Phi_w = \frac{4\pi I}{10} \times \frac{\mu\pi r_1^2}{l_1}$$

Writing $2\pi r/l_1 = \cos\theta$ and w = number of wires surrounding the cable, then the total flux along all the wires is

$$\Phi = 0 \cdot 2 I\mu w\pi r_1^2 \cos\theta/r$$

having a circumferential component (per cm axial length)

$$\Phi_c = 0 \cdot 2 I\mu w\pi r_1^2 \cos^2\theta/rl.$$

Neglecting the leakage from wire to wire, which must under the circumstances be comparatively small, the value Φ_c is that which was measured by Harvey and Busby. Now in case G the lay is $12\frac{1}{4}$ in., or say 12 times the pitch diameter, so that θ = about 75° and the circumferential component of flux per ampere in the cable calculated as above is $0 \cdot 000495\,\mu$, where μ is the real permeability of the armour wires. The test value for this flux is about 0·27, which would make μ about 546, a value that is quite possible. This is sufficient to check the probability of the assumptions just made and to prove the existence of a flux in the armour far greater than the circumferential flux.

5. Calculation of Armour Losses.

Adopting as a trial value $\mu = 500$, it should be possible to calculate the losses in eddy currents and hysteresis respectively and to compare the sum with the test-results. It should be remembered that with such values of μ, f and r_1 the product $r_1\sqrt{(\mu f/\rho)}$ cannot be regarded as small, and in consequence the flux distribution in the iron wire will not be uniform over the section and the calculation will be somewhat intricate. Moreover, since μ is not constant the result will be only a rough approximation, but having regard to the large ratio r/r_1 it is not unreasonable to treat each individual wire of the armour as a permeable conducting cylinder magnetized by an external force of value $H = 0 \cdot 2\sqrt{(2)} I \cos\theta \sin 2\pi ft/r$ parallel to the length of the wire and to calculate the resulting eddy loss by means of the Kelvin functions ber $[r_1\sqrt{(\mu f)/\rho}]$ and bei $[r_1\sqrt{(\mu f)/\rho}]$ *

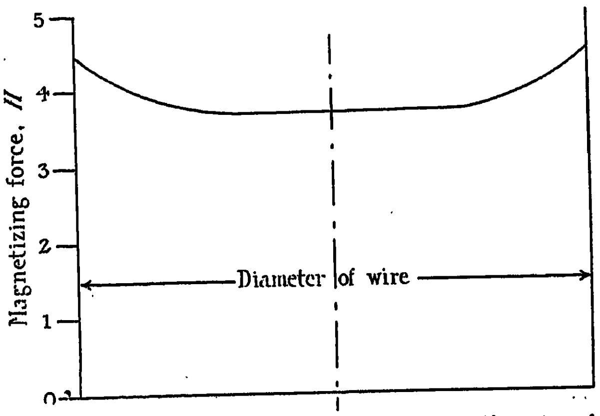

Fig. 1.—Variation of magnetizing force with diameter of armour wire.

For Harvey and Busby's case G, and with $\mu = 500$, ber$[r_1\sqrt{(\mu f)/\rho}] = 0 \cdot 8$ and bei $[r_1\sqrt{(\mu f)/\rho}] = 0 \cdot 8$ approximately, the corresponding differential coefficients being $-0 \cdot 4$ and $0 \cdot 8$ respectively.

Then the eddy losses per cm³ of iron are 0·0046 watt at 100 per cent of I.E.E. rating for the current in the core, corresponding to 0·0076 watt per cm length of cable. In the same way we may arrive at an approximate value for the hysteresis loss. For, writing $r_1\sqrt{(\mu f)/\rho} = x$, and $r'\sqrt{(\mu f)/\rho} = x'$, where r' is the radial distance measured from the centre of the iron wire, the magnetic density in the wire at radius r'

$$B = \frac{0 \cdot 2\sqrt{(2)}\mu I \cos\theta}{r} \cdot \frac{\sqrt{[\text{ber}^2(x') + \text{bei}^2(x')]}}{\sqrt{[\text{ber}^2(x) + \text{bei}^2(x)]}}$$

from which the distribution of flux over the area of one wire may be calculated (see Fig. 1). The variation

* Lord Kelvin: "Mathematical and Physical Papers," vol. 3; A. Russell: "Alternating Currents," vol. 1, ch. 16.

is not very great, but it is enough to make a sensible difference in the eddy losses compared with those calculated upon the assumption of constant density. The average value of B for test G is thus 2 418; whence taking a hysteresis coefficient of 0·003, and using the Steinmetz index, the watts dissipated in hysteresis per cm length of cable at 100 per cent of I.E.E. rating for the current in the core become 0·0064. Adding these to the eddy losses already calculated, we obtain $0{\cdot}0076 + 0{\cdot}0064 = 0{\cdot}014$ watt in iron loss per cm of cable. Now in test G, the difference between the a.c. and d.c. watts when 100 amperes were flowing in the cable was 12, and the length of cable was 26 ft. 7 in. Thus the watts per cm length of the cable were 0·014. This agreement seems to the author to be more than a mere coincidence; it appears indeed to justify the method of analysis and to prove the following points:—

(A) That the flux density in the armour is far greater than that based upon the circumferential flux as given by Harvey and Busby.

(B) That the consequent loss is at least largely due to hysteresis.

(C) That the eddy loss is due chiefly to currents concentric with the armouring wires, and not, as in the case of tubes, to currents flowing longitudinally.

6. Application to Low-Tension Cables.

Returning now to the 0·5 sq. in. lead-covered and armoured cable, we can calculate the loss in the armour on the above basis. With full I.E.E. rating (540 amperes) the result is:—

(1) Hysteresis loss per cm length	0·0854
(2) Hysteresis loss per cm² mean lead sheath surface	0·0088
(3) Eddy loss per cm length	0·1706
(4) Eddy loss per cm² mean lead sheath surface	0·0176
(5) Copper loss per cm length	0·1610
(6) Copper loss per cm² mean lead sheath surface	0·01658

The sum of (1) and (3) is 0·256, and we may roughly compare this figure with that derived from test G by increasing the latter in proportion to the square of the magnetizing force and to the volume of the armouring. This gives for test G, at full I.E.E. rating, 0·206, and at 150 per cent of that rating 0·3470; whence the calculated value is obviously of the right order, and out of all proportion greater than the loss in the lead sheath.

Thus we reach the following conclusion:—

> In low-tension lead-covered and armoured cables the loss in the armour is far greater than that in the lead, and is of such magnitude as to render the use of these cables impracticable for single-phase circuits unless special armouring of high resistance and low permeability is adopted.

With regard to the last suggestion, the case of mining cables calls for special comment, for an armour having a high resistance to eddy currents would almost certainly be impracticable from the standpoint of rule 125 (b) of the Mining Regulations.

7. Application to High-Tension Cables.

The case for high-tension cables differs from the above, due to the much larger ratio of diameter over armour to diameter of conductor. For example, assume that power at 22 000 volts is to be supplied by means of a pair of single-phase paper lead-covered and armoured cables. Then a 0·1 sq. in. cable with standard thicknesses of paper, lead and armouring would have an external diameter and size of armour wire almost the same as those of the 0·5 sq. in. low-tension cable which formed the subject of the last example. The core, however, being only 0·415 in. diameter will carry at most 191 amperes at full I.E.E. rating, and in consequence the maximum possible magnetizing force, the eddy currents and hysteresis losses are correspondingly smaller. The comparison is shown in Table 4.

Table 4.

Actual Losses per cm Length of Cable (spacing 2 in. centres).

	Cable size	0·1 sq. in. (h.t.)	0·5 sq. in. (l.t.)
Losses	(1) In the copper ..	0·1 watt	0·16 watt
	(2) In the armour (eddies)	0·021 watt	0·17 watt
	(3) In the armour (hysteresis) ..	0·016 watt	0·08 watt
	(4) Total armour loss ..	0·037 watt	0·25 watt
	Ratio (armour loss)/(copper loss), per cent	37	156

The loss in the lead is in both cases small compared with that in the armour, and consequently is neglected, but it is abundantly clear from the figures that a good commercial possibility exists for high-tension single-phase armoured cables. For if, in the case of 22 000 volts, the armour loss is only 37 per cent of that in the copper, it follows *a fortiori* that it will be still less with higher pressures where the insulation is thicker. Suppose, for example, that it were required to transmit 191 amperes at 132 000 volts by means of a pair of single-phase armoured cables, the pressure between core and lead being thus 66 000 volts. If we assume first that no intersheath is used and that the R.M.S. potential gradient is not to exceed 40 000 volts, the core will have to be hollow, of an area of 0·1 sq. in., having a diameter of 1·28 in. (3·3 cm). The internal diameter of the lead will be 3·52 in. (9 cm). Taking the thickness of the lead as 0·12 in. and the diameter of the armour wire as 0·104 in., with the usual allowances for bedding, the mean diameter of the armour becomes 4 in. (10·2 cm). Then assuming the same lay for the armour, with $\mu = 500$ and $h = 0{\cdot}003$ the losses per cm length of the cable at full load are:—

In the copper	0·1 watt
In the armour (hysteresis loss)	0·009 watt
In the armour (eddy loss)	0·008 watt
Ratio (armour loss)/(copper loss), per cent	17

This would not be a serious matter, and could in any case be easily compensated by increasing the area of the copper core from 0·1 sq. in. to 0·12 sq. in.; or by adopting an armour wire of special material.

8. Reactance of High-Tension Armoured Cables.

Harvey and Busby have called attention to the importance of the reactance drop in an armoured cable. They have indicated how this can be calculated for a cable enclosed by a tube, but the case of armouring is entirely different. The value of x, the reactance of a wire armour, can be calculated most easily by writing

$$x = \frac{2\pi f \Phi}{10^8 I}$$

where Φ is the flux produced by and encircling the current I.*

Thus if $H = 0{\cdot}2I \cos \theta / r$,

a = sectional area of one armour wire,

w = number of armour wires,

we have Ix = reactance drop per cm due to iron

$= 2\pi f H \mu a w 10^{-8}/l$

In Harvey's case G, with $d = 12$ in., at full I.E.E. rating from this formula

$Ix = 0{\cdot}012\ \mu$ volts per 100 yards of circuit due to the iron

and $Ix = 4{\cdot}8$ volts per 100 yards of circuit due to the air.

9. Impedance of E.H.T. Armoured Cables.

Now the energy voltage absorbed by the losses in the cable can be deduced from those losses as already calculated, and the resulting predicted impedance drop can then be compared with the measured value.

Thus in case G the calculated watts lost in the iron were 0·014 per cm at full load (97 amperes) and this has been shown to be substantially equal to the measured value. The corresponding loss in 100 yards of circuit is 260 watts. Thus this component of energy voltage is $260/97 = 2{\cdot}67$. The resistance of the same length is 0·085 ohm, giving an energy component = 8·25 volts. The total energy component should therefore be about 11 volts. The idle component due to the iron with $\mu = 500$ is $0{\cdot}012 \times 500 = 6{\cdot}1$ volts, and that due to the flux in air is 4·8, giving a total again of nearly 11. The impedance drop therefore is $11\sqrt{2} = 15{\cdot}5$ volts. The measured value is 16·5. This is certainly as near as one could expect from the nature of the calculations, especially when it is remembered that the tests in this case show a considerable variation in μ at about this current. Thus it may be said that the method of predicting the results again is justified and is consistent with all that has gone before.

If we take case E, a similar calculation shows that the predicted result agrees with the test figure if $\mu = 700$. With regard to the error in case G it should be remarked that analysis of the test figures indicates that the discrepancy lies in underestimating the idle component. This is without doubt due to neglecting the flux leaking from wire to wire along the armour, to which attention has been called earlier in this paper.

The above method may now be applied to ascertain the probable impedance drop at full load in the 132 000-volt cable. We have already found the energy losses per cm length to be 0·117 watt, so that the energy voltage-drop per cm is 0·117/191 = 0·000613, corresponding to 4·451 volts per 100 yards of circuit. Suppose the cables to be again 12 in. apart. Then the idle voltage component corresponding to the same length due to the flux in the air is 5·04 volts, while that due to the flux in the armour ($\mu = 500$) is 12·12. Thus the reactance voltage is 17·16, which when combined with the energy component gives an impedance drop of about 18 volts, or nearly 3·6 times as much as for the unarmoured cable. There is, however, no reason why such a pair of cables could not be laid close together, when the impedance drop could be reduced to about 14 volts per 100 yards' run, or say 25 000 volts (i.e. about 19 per cent) in 100 miles' run. This is not an impracticable figure; and we conclude as before that the presence of armouring is no bar to the successful application of lead-covered cables to e.h.t. transmission.

A far more serious question is the great capacity current inseparable from such a system. For on the assumption that the lead sheath and armour are both earthed, as would be necessary to prevent danger, the capacity of the paper-insulated 132 000-volt cables would be about 0·3 μF per mile. At 50 periods per sec. this means a capacity current of about 6 amperes per mile, or 1 200 amperes per 100 miles' run in a cable whose normal full-load current does not exceed 191 amperes. Special means would obviously have to be adopted to overcome this disadvantage, but such matters do not fall within the scope of this paper.

10. Effect of an Intersheath.

The introduction of a conducting intersheath reduces the diameter of the cable for a given voltage, and in consequence both the inductive and capacity reactances are somewhat increased. Thus cables with intersheaths are less favourable from the point of view of this analysis; not to such an extent, however, as to render them entirely impracticable. For while the loss per cm^3 of armour wire is somewhat larger, the volume of the armouring is distinctly less, so that the net result is only a small change. On the other hand, the intersheath is a help in dealing with the capacity currents. We may summarize our conclusions as follows:—

(1) Both the losses and the reactance due to the presence of armour wires about a lead-covered cable can be fairly predicted.

(2) Lead-covered armoured cables for single-phase low-tension transmission are impracticable on account of the large losses and high reactance introduced by the armouring, unless the armour wires be made of special material having very high resistance and low permeability. Such armouring, however, would be inadmissible under the General Regulations made under the Coal Mines Act, 1911.

(3) Lead-covered armoured cables for single-phase e.h.t. transmission are quite practicable in so far as losses and inductive reactance are concerned; but their high capacity when used for long distances would need special consideration.

* Russell: "Alternating Currents," ch. 1, p. 25.

DISCUSSION ON "RAILWAY ELECTRIFICATION IN FOREIGN COUNTRIES." *

WESTERN CENTRE, AT CARDIFF, 7 JANUARY, 1924.

Mr. J. W. Burr: It is obvious that this country is a long way behind in the matter of railway electrification, and this seems to be due to indecision as to whether single-phase, three-phase, or direct current should be used. I recently read a statement to the effect that a considerable reduction in the weight of locomotives was being brought about, and that a locomotive weighing about 60 tons could be made to give about 2 000 h.p. How does this figure compare with those mentioned by the author?

Mr. H. Kilgour: To the list of railways cited by the author might have been added one possessing some rather interesting features: this is the light railway running from Indianapolis to Rushville, a distance of about 45 miles. The motor coaches carry transformers and the motors are of the commutator type adapted to run on about 500 volts, either direct or alternating. Within the boundary of Indianapolis the supply is direct current, at the city boundary the supply is 3 000 volts (a.c.) and transformers are used, while at the Rushville city boundary the supply is at 500 volts (a.c.) and the transformers are cut out. The expresses make the journey in about 45 minutes, the right of way being private. The equipment was supplied by the Westinghouse Co. and, since I last saw the railway in 1906, has probably been considerably changed, as experience had even then shown that the motors suffered rather rapid deterioration and needed frequent attention.

Mr. S. B. Haslam: In 1901–2 I was connected with the Taff Vale Railway when that company were seriously considering the question of electrification, and, in association with the late Mr. T. Hurry Riches, the locomotive superintendent at that time, I went into the subject fairly closely. The outcome of careful deliberations was a decision that electrification was not suited for the short runs with very heavy goods traffic such as obtained in South Wales, but a sort of half-way system was adopted of running motor coaches on the line. The result of those deliberations was described in a paper read before the Institution of Mechanical Engineers.† At that time the only possible electrification was on the 500-volt d.c. system. In those days also the third-rail system was considered highly dangerous and the directors would not consider anything but the overhead line system, the cost of which on a 500-volt d.c. system put the matter right out of court. Recent investigations on the question have, however, shown the question in a very different light. It has always been a moot point among railway engineers as to how to deal with goods traffic in a district such as South Wales, in which the goods traffic predominates. Such runs as that from Cardiff to Penarth offer ideal conditions for electrification, and further up the Rhondda Valley it is surely a very different question, not so far as the actual running is concerned but as regards the collecting of the coal trains and the delivery and sorting of the empty trucks.

Major E. I. David: The decision of Sweden to adopt railway electrification was a sequel to the British coal strike of 1921. The Government of Italy was forced to take steps for electrification because of that strike and because of the abnormal prices of British coal which ruled in 1921. Switzerland's decision to electrify its railways was not prompted by commercial considerations but by a purely patriotic motive. The capital cost of most of its large hydro-electric stations was in the neighbourhood of £120 to £140 per kW, equivalent to a yearly capital charge of from £14 to £15. If the stations had been run on coal the capital charges would not have been more than £25 per kW installed. In fact, the actual running costs were higher after electrification than before. At the time that the Swiss railways were being electrified there was produced in that country a most efficient turbine-driven condensing locomotive. The turbine and gear were made at Zurich, and the whole equipment ran very smoothly. The air-cooled condenser was fixed in a cab at the back of the locomotive, and the vacuum was 27 inches when the machine ran at 40 m.p.h. The overall efficiency was about 70 per cent, an abnormally high figure for so small a turbine. As to the position of the South Wales railways, these short-distance lines, with fixed and definite gradients in the downward direction appear to be ideally situated for a system of electrification, particularly one which could employ regenerative control. The question of erecting super-power stations need not arise, because the stations of the South Wales Electrical Power Co. or other large private generating plants could be used without any restrictions. A system employed so successfully on motor-cars, namely, a driving motor at right angles to the axis of the axles, has not been attempted on railway work. From 400 to 500 h.p. has been transmitted in this way on some large racing cars and there seems, therefore, to be no reason why from 2 000 to 3 000 h.p. should not be transmitted in the same way. By this means absolute flexibility is obtained in a vertical direction. Variable-speed a.c. commutator motors have been used for electric winder drives giving regenerative control, and the only objection that I could raise was the large number of brushes (about 200 sets) on each motor. We are constantly being told that railway engineers have to solve most difficult problems, particularly in regard to suburban trains, the London Underground Railways being instanced. It is pointed out that the trains have to accelerate up to 30 or 40 miles in the space of $\frac{3}{4}$ mile and stop in another $\frac{1}{4}$ mile.

* Lecture by Dr. S. P. Smith (see vol. 62, p. 317).

† *Proceedings of the Institution of Mechanical Engineers*, 1906, pts. 3 and 4, p. 651.

The problem of the colliery winding engine is, however, that it has to accelerate to 60 m.p.h. and to come to rest in about 45 seconds over a distance of some 700 yards.

Prof. F. Bacon: The number of different electrical systems in vogue on the Continent is very large and it is useful to learn the circumstances which led to the adoption of those systems. I do not think that British engineers pay sufficient attention to what is being done in other countries. Apart from such men as the author, who pay frequent visits to European countries, the average British engineer has a habit of neglecting the lessons which can be learnt from Continental experience. I should like to ask the author whether he found the overhead constructional work on the Continent somewhat shoddy and of a kind that would not be tolerated in this country. Even such good engineering countries as Switzerland and Italy do not seem to have much respect for high-tension lines; they hang them up in the same casual way that we adopt in the case of telephone wires. It is difficult to see from the lantern-slides of the driving mechanisms how the flexibility is obtained. With these arrangements of links and cranks is there ever any difficulty in starting?

Mr. W. Nairn: In dealing with the question of substations and the transformation of high-tension three-phase currents to direct current, Mr. Roger Smith in a recent paper mentioned an apparatus which he called a transverter. I should be glad if the present author could give any information as to this.

Mr. W. J. Bache: Is the connecting-rod system of drive being superseded simply because the geared drive offers greater advantage, or are the inherent faults of the connecting-rod drive the cause of it being substituted by the geared system?

Dr. S. Parker Smith (*in reply*): With reference to Mr. Burr's remark, it might be mentioned that three-phase locomotives weighing 60 tons and rated at 2 000 h.p. were working in Italy as long ago as 1909. It is well known that the weight per horse-power in three-phase locomotives is very low, but great advance in this direction with other types has resulted from the adoption of gearing and high-speed motors.

Mr. Kilgour cites an interesting case of a light railway in the United States worked on a mixed system. In some cases these have been converted to d.c. working—the system that should have been adopted from the outset for the prevailing conditions.

The lecture was confined chiefly to main-line working. As Mr. Haslam says, views regarding the use of a third rail have changed greatly since 1901–2. An overhead line with 500 volts would be generally condemned. Possibly the present-day solution of his problem would be a d.c. system with third rail and locomotives, while battery locomotives would be used for shunting, etc.

Major David's figures illustrate well how much countries are now prepared to pay for economic independence. The high cost of Swiss stations was doubtless due in great part to the war, but probably the annual capital charge would be less than the figures given owing to the long period taken for repayment of hydro-electric works. Experiments are being made with a driving motor at right angles to the axis of the axles, but results do not appear to be forthcoming as yet.

In reply to Prof. Bacon's question, the overhead constructional work on Continental railways is usually of a lighter type than that met with here, though, generally speaking, it would be going too far to call it shoddy. Flexibility in the driving mechanisms is usually obtained by mounting springs inside the pinions of the gearing.

Replying to Mr. Nairn's question, as far as the lecturer is aware the transverter is not yet out of the experimental stage.

The geared locomotive, referred to by Mr. Bache, finds favour because the high-speed motors used with it lead to reduced cost and weight.

DISCUSSION ON

"PULVERIZED FUEL AND EFFICIENT STEAM GENERATION." *

WESTERN CENTRE, AT BRISTOL, 4 FEBRUARY, 1924.

Mr. A. J. Newman: I am convinced that one of the great reasons for the large development of pulverized coal in America can be traced to the fact that some of the larger concerns want large boilers, and I think it is the largeness of the boilers rather than the greater efficiency that has tended to develop other means of firing than mechanical stoking. My own view is that the alteration of existing plant seems impossible on account of the large furnaces that are necessary with pulverized coal. I feel that there is more than a little danger from ash and clinker troubles, but the author states that this has been removed by the introduction of a water screen, and that there is no slagging is certainly a point in favour of the Lopulco system. The figure given by the author of 2·5 per cent ash emission is, in my opinion, very low. In existing plants it is almost impossible to bring it down to 2·5 per cent.

Mr. W. E. Hardy: When reading the paper I had some difficulty in reconciling some of the author's remarks. In the summary prefacing the paper he says: ' The author is of opinion that the advantages in the aggregate of pulverized fuel are so great that they constitute almost a revolution in steam-boiler practice." Then under the heading of "Conclusion" he says: "It is, therefore, not altogether an easy problem to decide whether for a new plant pulverized fuel should be used in preference to mechanical stoking." Again, in speaking of a number of the big American stations, he states that " the decision to adopt or reject pulverized fuel has in a number of cases been a very close one." The author has, however, now definitely stated that he is in favour of pulverized fuel. In the last Annual Return made by the Electricity Commissioners the best overall efficiency of any power station in Britain is given as 17·8 per cent. Can the author say what is the figure for the Lakeside station?

Mr. J. W. Fidoe: The boiler plant described is in essentially larger units than that used in the majority of power stations, and this factor may to some extent affect the comparison of results. The minimum size of boiler for which the central pulverizer system is suitable appears to be between 50 000 and 80 000 lb. of steam per hour, but the units described are much larger. Boiler efficiency is limited by unburnt coal in the ashes, and by radiation and heat lost in the chimney gases, and as it does not seem possible to reduce these losses below 8 per cent the results stated represent a near approach to economic possibilities. The large combustion chamber with its double walls is a new feature permitting pre-heating of the air and at the same time reducing radiation loss; the application of double walls to boilers fitted with mechanical stokers is well worth consideration, since air leakage in boiler settings is one of the difficulties in the way of maintaining high efficiency. The ash and clinker produced in the combustion of coal is a problem which the users of mechanical stokers have to consider. Coals with a high ash content can be burnt successfully if the clinkering is not excessive, but it appears that by pulverizing the fuel inferior grades can be burned, provided the volatile matter is not too low. The melting point of the ash in coal is a chemical question, and in the use of mechanical stokers is generally ignored, but by taking samples and analyses of the ash much trouble can be avoided and higher boiler efficiencies obtained. A coal having an ash high in silica and low in bases, or vice versa, does not readily clinker, but if mixed with another coal containing ash of different composition troublesome clinkering will occur. The use of the water screen in the bottom of the combustion chamber indicates a preference for a coal with a fusible ash, and I should like to ask if this is so. In previous experience with pulverized coal firing of boilers much trouble has been caused by dust being blown out of the chimneys, and one large plant in this district had to be shut down on that account. The explanation given as to the dust produced being of so fine a character as not to settle within a wide radius of the boiler house is very interesting, but will need further confirmation before it can be generally accepted. The use of mechanical stokers has been hampered in the past by the limitation of width to about 8 ft., rendering several grates necessary if large boilers were to be used. The construction of the firebrick arches presented a serious drawback to greater widths of grates, while the necessary division walls meant a loss of 18 in. in width of furnace for each stoker, with consequent reduction of grate area and coal burnt. The flat suspended arch has removed the trouble with the brickwork, curved surfaces and division walls being no longer required, but there is still a limit to the width of the ordinary mechanical stoker. At the present time a new type of stoker with a width between side walls of 12 ft. is being installed locally, and, judging from its design, there does not appear to be any mechanical obstacle to making grates of double that width with an area of over 500 sq. ft. in a single unit. Progress on these lines will provide a formidable competitor in the firing of large boilers, as the cost of setting and driving equipment should be less than for the pulverizing system.

Mr. W. Nairn: I had occasion to burn oil fuel during the coal strike of 1921 and, as it was not a commercial proposition to continue on oil when coal again became available, I considered whether it would be possible to use pulverized coal in the oil furnaces. I found, however, that the combustion space was much too small to permit of the use of pulverized fuel, and

* Paper by Mr. D. Brownlie (see vol. 62, p. 385).

accordingly mechanical stokers were re-installed. I mention this fact to make it clear that there are very few boiler plants in the country to-day with settings suitable for pulverized fuel and one hears of proposals to install pulverized plants on Lancashire boilers, a duty for which they are quite unsuitable.

Mr. T. Hood : The question of fuel economy is one that every engineer should have at heart. My knowledge of local affairs confirms the author's remarks respecting the serious waste that is prevalent. In a certain colliery not far from Bristol, using Cornish boilers and non-condensing engines with steam at 60 lb./sq. in., the fuel consumed is one-third of the total coal wound from the pit. On the other hand, the consumption at the Great Western Colliery, Pontypridd, is, I believe, 2 per cent of the total coal wound. It would appear that colliery owners are not entirely blameless in this vital question. There are many technical institutions such as those in London and Sheffield where fuel technology is closely investigated, and I should very much like to see established, all over the country, centres at which any industrial owner could apply for guidance respecting the virtues of different kinds of apparatus that are claimed to increase boiler house efficiency.

Mr. R. Hodge : In view of the author's statement that the approximate cost for large stations employing pulverizing plant is about equal to that of mechanical stoking plant, it would be interesting to have his opinion as to what the percentage increase (if any) in prime cost would be for a new station employing three 5 000-kW turbo-alternator sets, assuming the steam consumption to be approximately 11·5 lb. of steam per kWh on boiler plant working at 200 lb./sq. in., the total steam temperature being approximately 600° F.

Mr. H. F. G. Woods : The point in the paper which particularly impressed me was the possibility of using the bye-product breeze of the low-temperature carbonization process. In this connection it would be interesting if the author could state the minimum volatile percentage with which the Lopulco system will satisfactorily deal, since, as there does not appear to be any immediate prospect of obtaining large and regular supplies of low-temperature coke, it would seem that a most advantageous application of that system would be to employ it for the use of coke-oven breeze. With regard to the first cost of the pulverized fuel system as compared with that of a plant employing mechanical stokers, the cost of buildings in each case must, of course, be taken into account. The great height of the boiler houses necessary with plants employing the Lopulco system must make a heavy additional cost which will be a serious offset against the undoubtedly numerous advantages of the pulverized-fuel system. It would be instructive if the author would give some indication of the extent to which the cost of buildings is affected by the installation of pulverized-fuel plant.

Mr. D. Brownlie (*in reply*) : Many of the points raised have already been dealt with in my general reply to the whole of the discussion, but I would say very briefly that pulverized fuel is a revolution in steam generation because it has altered entirely all our views on the subject and has also resulted in great improvements in the competitive system of mechanical stoking.

Since the paper was written, boiler plant efficiencies as high as 92·5 per cent are being obtained in the United States with both methods of firing, and I believe that the overall thermal figure at Lakeside is approximately 17 250 B.Th.U. per kW, although it must be remembered that this covers many items other than merely steam generation and pulverized fuel. Finally, mechanical stokers are now being constructed up to 24 ft. in width because of the developments of the suspended arch, and, so far as I know, the Lopulco system will burn fuel containing as low as 3 per cent volatile matter.

DISCUSSION ON "THE DESIGN OF APPARATUS FOR THE PROTECTION OF ALTERNATING-CURRENT CIRCUITS." *

WESTERN CENTRE, AT PLYMOUTH, 17 APRIL, 1924.

Mr. W. Nairn: The most important application of the author's system is the complete protection of any feeder or distributor in the most complicated networks. Such protection in the case of ordinary three-core cables has until now been obtained with the Merz-Price system of protection, and one of the principal objections to this system is the difficulty of balancing the transformers. This difficulty leads to the irritating opening of healthy sections during the passage of fault currents and also entails extra work when cutting in a new substation on a ring main. If the new substation B was between substations A and C, the transformers in C have to be removed to B to balance with those at A and a new set of six transformers have to be installed at B and C. To make the protective gear completely reliable, I should like to know if the author has any suggestion to make for the supply of current for the tripping circuits in substations. This supply is now often taken from primary batteries; these require an inordinate amount of supervision and, if this is not given, the protective gear may fail at the crucial moment and the benefits of protection will be nullified.

Mr. H. F. G. Woods: I am of opinion that systems employing pilot wires should be avoided in connection with the protection of transmission lines, since the pilot wires themselves constitute a source of weakness which adds additional risk to the continuity of the supply. Personally I believe that the plain straightforward overload and reverse-current protection of parallel feeders is preferable to the use of a system employing pilot wires, although the objection to the former is that it is not in all cases sufficiently discriminative. The author's system of biased relay protection introduces a stabilizing factor which would appear to have done much to solve the problem of providing efficient protection without pilots. The system also offers the advantage that it is possible to tap off small loads at intermediate points on parallel feeders. The switchgear shown on the lantern slide is now being erected in the main substation at Torquay, and the author's system of feeder protection is being used in connection with it to protect two parallel feeders between that substation and the power station at Newton Abbot, about 7 miles away. At an intermediate substation about half way between Newton Abbot and Torquay, a supply is being tapped off each line alternatively to the extent of some 200 kVA.

Mr. J. H. Thomas: It seems to me that the introduction of the biasing transformer, which is the chief point of novelty, is adding a good deal of complication without giving sufficient compensating advantages. The biasing principle has been generally applied in connection with relays and is, I believe, a satisfactory method. The particular relay which I have in mind is the McColl relay, in which the biasing can be done either mechanically, the bias being obtained by adjusting the balance of the beam, or electrically. Referring to Figs. 6, 7 and 9, the biasing transformer does not appear to have much advantage over the use of biased relays. The phantom switch arrangement is certainly very ingenious. With regard to the use of biasing transformers with split-conductor systems, it seems to me again that they add an additional complication without sufficient compensating advantages, and it is sometimes said that the ordinary arrangement is too sensitive. The later figures in the paper seem to be very complicated, and it must be borne in mind that the internal connections of the biasing transformers are not shown in these. It seems to me that we should endeavour to use the simplest possible arrangement utilizing standard and strong apparatus.

[The author dealt with the questions raised in this discussion in his reply published in the *Journal*, 1924, vol. 62, p. 619.]

* Paper by Mr. A. S. FitzGerald (see vol. 62, p. 561).

DISCUSSION ON

"POWER CIRCUIT INTERFERENCE WITH TELEGRAPHS AND TELEPHONES." *

NORTH-EASTERN CENTRE, AT NEWCASTLE, 10 NOVEMBER, 1924.

Mr. W. T. Dalton: I recognize some of the rotary converter tests as being those taken on the Newcastle machines when I was present, and I should like to mention that the diagram and description of Prof. Miles Walker's method for ascertaining the pitch note (vol. 62, p. 843) was employed by him during the tests and investigations which were carried out on the converters to which I refer. The bottom oscillograph in Fig. 14, showing converter No. 1 running alone, was taken after this machine had been altered as the result of the tests referred to in the paper. The work of altering the main poles was carried out in our own workshops, all north poles being moved 0·419 inch in one direction and all south poles the same distance in the opposite direction, thus giving alternate wide and narrow gaps between adjacent poles. The commutating poles were not altered. The commutation of this machine after the alterations was unaffected and it ran perfectly. Converters that have since been ordered of the same kilowatt capacity have been constructed with the same arrangement of pole spacing. It must not be argued from this that the same treatment could be applied to all machines, as some later rotary converters of smaller size and different speeds were supplied with the main poles skewed only, with satisfactory results. Referring to Fig. 15 (No. 4 rotary) no explanation is given as to why the current in the negative cable is greater than that in the positive cable. The positive and negative sides of this machine are each connected to the switchboard by two 0·750 inch cables in parallel. Mr. Aldridge mentioned in the London discussion that the curves marked 15 (Fig. D) were taken simultaneously each from 100 turns of wire wound directly over the respective cables. With two cables in parallel, however, the total current of the machine may not divide equally between each cable, due to a possible difference of contact resistance at the terminals. Whether this is the correct explanation could only be proved by repeating the test with the 100 turns of wire embracing both parallel cables on the positive and negative sides respectively. Interference on telephone and telegraph lines may be classed under three headings: (1) Earth current interference, (2) induction interference, and (3) electrolytic action on underground cables and pipes. Some 24 years ago I was present at some tests on an overhead telegraph line where it was alleged that a tramway running parallel with it caused disturbances. A special car was run when the rest of the system was shut down, and the times of switching the car controller on and off, and the times of the kicks recorded on the tape of the siphon recorder connected to the telegraph line, were found to coincide. This was a simple problem, as by duplicating the line, thereby doing away with the earth return, the trouble was overcome. This shows that the interference was due to the telegraph line being in electrical contact with the power lines, not through any fault, but simply because both parties were using the earth as a return. Tramways in this country, however, are constructed with an uninsulated return, and I do not see how they could be run otherwise except at great sacrifice of efficiency, but I should like to ask the author if, having regard to the great development of electrical power that is now taking place in this country, he is able to predict that the future will see a telephone system designed with its lines and all parts of its equipment insulated from earth. Such a desirable state of affairs would remove much of the trouble from which modern telephone systems appear to suffer. I agree that we must try to appreciate each other's difficulties with a view to solving these problems of interference, but it is unfortunate that in the development of the rotary converter and modern telephone systems the designers of each appear to have unintentionally reached a state of affairs whereby the former creates disturbances for the latter to receive with such completeness that had they deliberately set out to achieve this result they could not have been more successful. This paper will cause future users of converters to insert clauses in their specifications to provide for the machines which they purchase being free from the liability of causing interference to telephone and telegraph lines, and had some of the information contained in the paper been kept less secret when converters were first found to give trouble due to tooth harmonics it would have warned designers and purchasers of what they should guard against, in which case some of the later machines might never have had to be altered. Some of the converters referred to in the paper had been in service five or six years before any complaint was made as to their causing interference, and power undertakings do not welcome the suggestion that they must pull their plant to pieces and reconstruct it. The author, in replying to a speaker in the discussion at another Centre, appears to regard the risk of interference due to electrolytic action as being serious. While there may be isolated cases of such trouble, I do not think that there is much danger to be feared from this cause on British tramways. If there is any doubt as to the correct disposition of the negative feeders on a tramway, investigations may be carried out by constructing a model of the system. A suitable room should be available where a skeleton map of the system can be chalked on the floor. (A convenient scale would be 4 ft. to the mile, or 1/1 320th.) The track and negative feeders would be constructed of wire of correct

* Paper by Mr. S. C. Bartholomew (see vol. 62, p. 817).

resistance (to scale), the former being pinned to the floor over the chalk lines, care being taken to see that all the joints were carefully soldered. The negative feeders would be made up as wire spirals, each having a resistance equal to the value of the corresponding feeder multiplied by 1 320. The method of loading up the track would be obtained by taking average readings from all the feeder ammeters in the power station or substations and dividing by 1 320. Current representing the tramway load could be fed into the various routes, and the model then explored with a voltmeter. The results can be compared with the voltmeters on the Board of Trade panels, and the negative cables on the model may then be altered to meet any desired conditions. It is possible to imitate the boosting of the rails on such a model. The rails of a tramway system with the negative cables form closed circuits of low resistance, and the current values follow Kirchhoff's law of superposed currents. There should therefore be no difference of voltage between the various points on the rails where the negative cables are connected to the rails. Any such negative point that is at a higher potential in relation to another negative point should have the corresponding feeder increased in section, or the negative points at lowest potential should have resistance inserted.

Mr. F. G. C. Baldwin: The subject dealt with is one which has been regarded by many as most contentious, and it is one upon which widely different opinions have been expressed. It is, however, a fact that the problem is equally important to electrical engineers generally, both those engaged in the lighter and those in the heavier branches. Although different interests are concerned and divergent views are held, it is pleasing to testify to the very amicable relationship which obtains in this district between engineers of the Post Office and of power supply and electric traction undertakings, and which the activities of the Institution have done much to engender. The problem of interference, serious as it is at present, is likely to become of even greater importance as the telephone and telegraph and electric power supply systems develop, a development which all electrical engineers are anxious should take place in the fullest measure. To the interference already experienced in ordinary telephone and telegraph working must now be added the possibility of interference to broadcasting. There are now approximately a million listeners licensed to receive broadcasting, and it is essential that their interests should be safeguarded. It would seem that the increase of extra-high-tension overhead lines may be injurious to undisturbed reception in broadcasting, by reason of the fact that such lines virtually constitute transmitting aerials. Can the author say if any cases of interference to broadcasting from this cause have occurred, or if interference is anticipated? It is customary, and perhaps not unnatural, to chafe under control, but attention is drawn to the chaos which has resulted in America from the absence of suitable control in regard to broadcasting and to the contrast between that state of affairs and the far superior arrangements in vogue in this country. This has a parallel in the matter of interference. It is believed that in America it has been necessary to set up numerous committees throughout the United States for the purpose of dealing with local questions of interference. In this country the services of such committees have been rendered unnecessary by the system of control which is in operation.

Mr. C. Whillis: The author apologizes for presenting certain portions of his subject matter in an elementary way, but no apology is needed in this connection. If co-operation is to be effective, each side must understand the problems with which the other contends, and in my experience this is just the rock on which co-operation is likely to split. The power engineer, for example, has difficulty in realizing the extreme sensitiveness of a telephone receiver, while the telephone engineer labours under a similar disadvantage with regard to many power problems. Such difficulties are very clearly dealt with by the author and it is quite certain that his paper, carefully studied by both the interested parties, will go a long way to produce that sympathetic appreciation of mutual difficulties which is essential to successful co-operation. Fig. 18, which shows the twist system of transposition of communication line wires, does not tell the whole story. A uniform system of this kind is satisfactory for circuits of moderate length and light gauge, but with long circuits of heavier gauge, trouble is experienced between contiguous groups, and it is necessary to introduce transposition crosses in addition. Should power circuits exist alongside sections of a long route, tertiary effects would accentuate this trouble. For the reasons stated in the first paragraph on page 840, I think that it is somewhat dangerous to set up different standards of permissible interference for telephone and telegraph routes. In this country telephone and telegraph circuits are so intimately associated, both on open routes and in cables, and main routes are so interconnected with cross-country routes, that the risks of tertiary effects are very great. On page 846 the author indicates that extremely high voltages are in some cases impressed on communication lines. It would appear that such voltages might be a source of danger not only to internal plant but also to men working on communication lines at points remote from the existing power system. Have any such cases arisen in this country?

Mr. R. W. Gregory: Mr. Dalton has mentioned his experience with a machine which, after running without causing interference for five or six years, became a trouble to the telephone system when changes in design were made to the latter. This, of course, shows us that it is advisable to look to the future. It is quite certain that, if this country is to be "electrified," we must look for large developments in the mileage of overhead power lines during the next few years, and at the same time we must expect a large increase in the number of telephone subscribers in the country before "saturation" is reached. Moreover, I take it that the tendency in telephony, as in power supply, is to increase the amount of automatic apparatus. I should be glad if the author would say whether the automatic telephone systems which may be adopted in the future are any more liable to interference than the existing manual systems, and also whether any

special precautions against interference are necessary owing to the use of automatic telephony.

Mr. H. Kitchen: The balancing of lines and apparatus is common to all metallic circuits installed by the Post Office Engineering Department, and every care is taken to eliminate electrical disturbances from outside sources. Whether these methods are successful or otherwise, the public is left to judge. Recently a valve amplifier has been introduced by the Post Office, and this device can be attached to any subscriber's telephone. This innovation is a boon to those who are somewhat deaf, but it has the drawback inherent to all amplifying devices, that it not only amplifies the sound waves but increases other noises. Minute disturbances, which are not noticeable on a long trunk circuit under ordinary conditions, become audible when an amplifier is used, and the elimination of extraneous noises becomes a more pressing proposition. Mr. Gill's Presidential Address quoted by the author has already borne fruit, and a committee of telephone experts from most of the European countries has decided upon a programme of long trunk lines, which will place England in communication with places as far distant as Genoa and Madrid. The problem of the elimination of disturbances due to electric tramways, railways and other systems will be a very difficult one. Can the author say whether any special measures have been decided upon?

[The author's reply to this discussion will be found on page 394.]

North Midland Centre, at Leeds, 9 December, 1924.

Mr. W. E. French: I should like to supplement the author's remarks on slot harmonics by some facts which may not be common knowledge; any statement on slot harmonics is of importance, as they seem to be among the main offenders in power-circuit interference. Before dealing with these harmonics proper, it is necessary to touch on "phase-changed" higher harmonics, which Zenneck first observed with the simple

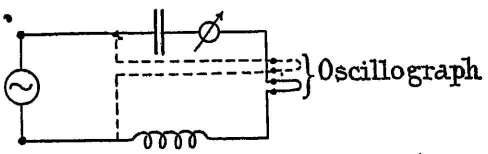

Fig. H.

experimental circuit shown in Fig. H. A circuit containing capacity and self-induction in series is connected to the terminals of an alternator. The wave-shapes are taken by an oscillograph. By choosing suitable values for the adjustable capacity and self-induction the natural frequency of this circuit can be tuned to any harmonic present in the generator. In this way it

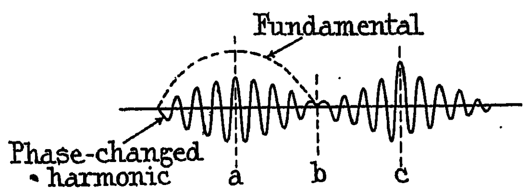

Fig. J.

becomes possible to sift out any desired harmonic, and subject it separately to investigation. They will mostly appear as pure sine waves and are classed as normal harmonics. There are, however, other harmonics possible (shown in Fig. J), and known as abnormal harmonics. It will be noticed that after one-half of the fundamental period has elapsed, a phase-change of 180 degrees in the E.M.F. or current wave has taken place at a time indicated in the diagram at "a." From here onwards there exists in the resonance circuit an E.M.F. which is in opposition, and which gradually reduces the amplitudes to zero; this occurs at the point "b," where the phase-change becomes definitely visible. An inspection of Fig. J might suggest that this curve is the resultant or beat curve of two having different frequencies. This is not the case, and there is only one single harmonic present. Such phase-changed harmonics have been investigated by Zenneck and Rogowski, and a very complete discussion will be found in *Annalen der Physik* (1906, vol. 20). The next step is to show that such abnormal harmonics may be present in generators. In most textbooks the calculation of the induced E.M.F. is based on a distribution of the flux densities such as

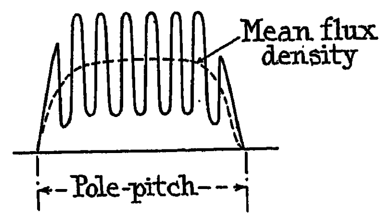

Fig. K.

occur with smooth-core armatures; this is somewhat misleading as it tempts the unwary to overlook the influence of the field fluctuations. The latter are a result of the varying values of the permanence as slots and teeth pass a given point of the pole shoe. The field curve will in reality assume a shape similar to that shown in Fig. K. The field curve has decided higher harmonics with amplitudes varying about the mean curve of flux density, the latter serving as the basis of calculation of the generated electromotive force. The period of these harmonics depends on the slot pitch, and their frequency can be calculated from the relation given by the author, viz. $F = N \times S \times R/60$. Their amplitude must depend on the relative values of width of tooth, teeth saturation and radial length of air-gaps. It is not unusual to design alternators with an even number of teeth per pole. The result is that the higher harmonics will also be even. On the other hand it is well known that normal, even harmonics can have no existence in the wave-shape of such machines.

Therefore tooth ripples of an even order can enter into the alternator wave-shape only as phase-changed higher harmonics, when the symmetry of the alternator wave is preserved. The presence of the phase-changed harmonic may be explained as follows: Let there be a whole number of slots per pole arc in Figs. L (*a*) and L (*b*). In the position " a " the number of flux-carrying teeth is a minimum, while in position " b " that number becomes a maximum; thus the permeance of the main flux undergoes considerable periodic fluctuations. Hence the main flux will be subject to periodic variations, the period of each change corresponding to the slot

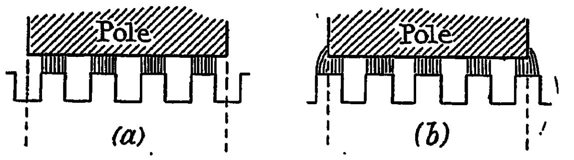

FIG. L.

pitch. These flux pulsations will be most effective when coil centres and pole centres coincide. When the coil sides are under the pole centres the flux pulsations will be of minimum effect. The flux pulsations are of the same phase, but of opposite sense under consecutive poles. The position of centre-line coincidence of coil and pole being that of maximum flux linkage with respect to the higher harmonics, their maximum voltage will be induced in this position. As the coil travels in the direction of the arrow (Fig. M) the coil linkage with the flux pulsations will decrease until zero linkage is reached in the neutral zone. The resultant E.M.F.

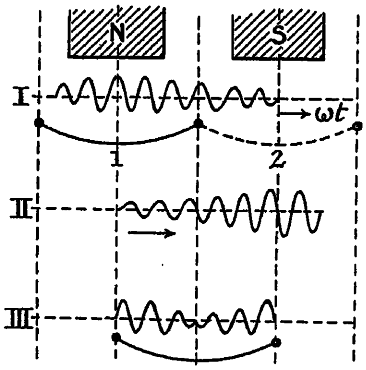

FIG. M.

curve so obtained is shown in Fig. M, I. Simultaneously, as the coil passes from right to left, it will gradually be subjected to the influence of the south pole until the coil centre reaches mid-pole position south. The resulting E.M.F. curve is shown in Fig. M, II. If these two curves are superposed, the E.M.F. curve due to the field pulsations is found, and is shown in Fig. M, III. This curve is obviously a phase-changed higher harmonic as demonstrated by the experiments of Zenneck. The influence of this harmonic on the fundamental E.M.F. wave is comparatively small. In this connection it must be remembered that the phase-change takes place when the coil sides are in the centre-pole position. As this is also the position of maximum E.M.F. of the fundamental, the phase-change of the harmonic will occur near the minimum value of the fundamental E.M.F. wave. Superposing the higher harmonic on the fundamental in this sense (Fig. N) it will be seen that its effect is not marked, and that the resulting wave closely

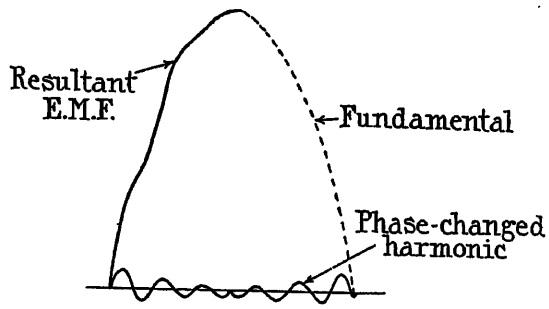

FIG. N.

approximates to a sine curve. Another case may be cited, when the pole arc contains a fractional number of the slot pitch [Figs. O (*a*) and O (*b*)]. Here no pronounced variation exists in the permeance of the main field, the number of flux-carrying teeth remaining sensibly the same. An inspection of the positions

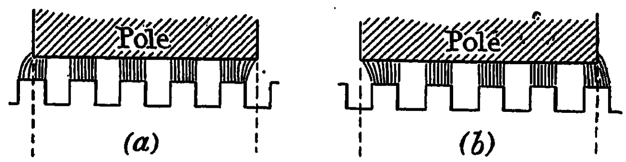

FIG. O.

[Figs. O (*a*) and O (*b*)] will show the possibility of a flux-swing in a direction opposite to the armature rotation. This oscillation must have a maximum effect on the coil sides which are in the centre of the poles, thus producing a phase relation of the phase-changed higher harmonic with respect to the fundamental wave, which is

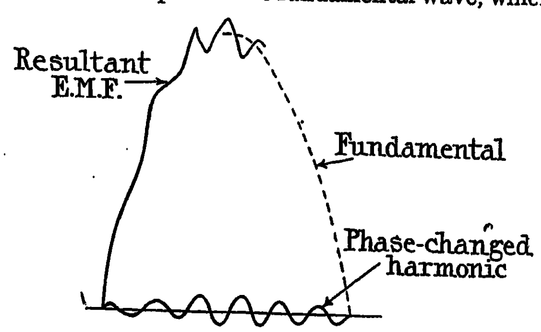

FIG. P.

exactly opposite to that in the previous case, i.e. the phase-change will occur in the neighbourhood of the maximum of the fundamental wave. Again, superposing the higher harmonics on the fundamental in this sense (Fig. P), it will be observed that its effect is considerable. These harmonics are also present in non-salient-pole alternators. The remedies are similar in both types of

machines, viz. high tooth saturation, relatively large air-gaps with small slot-openings; in salient-pole generators a pole arc which is as near as possible a whole multiple of the slot pitch; with non-salient-pole machines a different number of teeth in rotor and in stator. Another method is the "skewing" of the field, mentioned by the author as applicable to the salient and non-salient types for the suppression of higher harmonics. In conclusion I would suggest the following additions to the author's bibliography:—

WORRALL, G. W., and WALL, T. F.: *Journal I.E.E.*, 1906, vol. 37, p. 148.

ZENNECK, J., and STRASSER, B.: *Annalen der Physik*, 1906, vol. 20, p. 759.

ROGOWSKI, W.: *Ibid.*, 1906, vol. 20, p. 766.

ARNOLD, E., and LA COUR, J. L.: "Die Wechselstromtechnik," vols. 4 and 5.

Mr. G. W. Hammond: In case it may be thought that to some extent the Post Office maintenance may be at fault, I think it worth while to mention that so far as overhead lines are concerned a very high standard is set up, and in the case of underground cables a standard of no less than 10 000 megohms per mile of wire is insisted upon before the cables are accepted from the contractors. I have in mind one of the earlier cases of the high-tension power lines constructed in this district, where there are road crossings and the power wires at the crossings are carried on the same poles as the main trunk line. Interference in the nature of a high-pitched note was reported on a circuit some 200 miles in length, and it was finally located to a section of line 10 miles long. Careful investigation was made on this stretch of route, and the trouble was definitely established to originate at a joint power pole crossing. The line conditions specified for such crossings are that the power wires should cross at right angles to the main trunk lines, but owing to physical difficulties it was not possible to attain the ideal at this particular point. The high-tension wires approached the trunk line at an angle approaching 60°, and the same physical difficulties caused the Post Office construction to be imperfect in the matter of symmetrical twist. The resulting defect was this high "singing" note, which was, I think, "D" in the second octave above middle. We overcame the difficulty as a temporary measure by running over the four spans a length of lead-covered 1-pair cable of 40 lb. conductor, the lead covering acting as a screen and giving the required immunity from interference. The transmission was degraded by reason of the harmonic from the high-tension supply. It was less degraded by the introduction in the particular case of the short length of lead-covered cable. I have in mind a case more recent than the one I have just quoted, of a London line running to an East Coast town. That would appear to be sufficiently remote from the West Riding, but the circuit was routed via a main cable passing through Leeds. The main cable had a high order of insulation, in the neighbourhood of 18 000 megohms per mile. It was balanced for wire-to-wire and wire-to-earth capacity, and was loaded with impedance coils to neutralize the capacity effects. A high note was observed on this particular circuit, and it became intolerable, or at any rate the disturbance was amplified, due to the fact that the circuit was in repeater at Birmingham and at Leeds for the purpose of improving the transmission. In improving the transmission we also amplified the disturbance. This disturbance was finally and definitely found to be brought into the cable from an overhead line which ran parallel for a short distance to a West Riding traction system. So far as the other circuits on that particular overhead route were concerned, some disturbance was noticeable, but it was not of such a pronounced character as that which was reported in connection with the long-distance circuit. The two instances I have quoted may be thought to be exceptional, but there are quite a number of circuits which are to some extent degraded in transmission but which are not sufficiently interfered with to warrant them being reported by the Post Office Traffic Department.

Mr. W. R. T. Skinner: I should like to have the author's opinion as to the use of drainage coils on telephone circuits for the purpose of keeping down to a reasonable value the average potential of the latter with respect to earth. This is particularly necessary in connection with communication circuits supported on poles carrying power lines working at high voltages, as, in such cases, it is not uncommon for excessively high and dangerous voltages to be induced in the communication circuits unless some method of reducing the potential is adopted. If repeating coils are used at the instruments and the distance between the latter is not very great, the centre point of the winding connected to the line can be earthed and drainage coils, as such, eliminated, besides introducing additional protection in the form of insulation between the two windings of the repeating coils. There may be a slight objection, from the operating point of view, to the transposition of power lines, in that with a transposed system it is not quite so easy to follow one particular wire, when making a pole-line inspection from the ground, as it is when the wires maintain the same relative positions throughout the length of the line. In this connection, if transposition is not resorted to, it is, I believe, better to adopt a triangular spacing of power wires rather than a horizontal or vertical spacing. Of the two last-named arrangements probably horizontal spacing is the better if the communication circuit is carried beneath the power wires on the same poles, as it would appear to give a better balance of line constants. It is fortunate that both the communication engineer and the power engineer are interested in the removal of harmonics and the elimination of residual currents.

Mr. A. C. Mayman: In investigating a case of disturbance recently I noticed one effect which does not appear to be mentioned in the paper, namely, the inductive effect seemed to have two components. There was a high singing note due to slot harmonics, which did not seem to give much cause for complaint as speech could take place without interference. In addition, however, the rising note of a car motor was superimposed. A tramway system was concerned and the cars climbed a stiff hill. When they were fairly

well loaded, on going up this hill they created a disturbance which was more pronounced than the high harmonic note. I should like to ask the author whether the elimination of the high note will bring in its train the elimination of the rising note due to the car motor, and, if not, what he would suggest would be the best course to adopt. It would appear that the flux thrown out by the harmonic is the cause of the car pulsation being carried into the telephone line.

Mr. J. W. J. Townley: The particular aspect of the paper that appeals to me is the question of responsibility for dealing with the troubles which the author describes. The individuals responsible have been placed in the following order, the designer, the power engineer, and the Post Office engineer, but I would suggest that these three be bracketed together, because however much we may take care of power plant that is now being put down, or will be put down in the future, to eliminate possible causes of disturbance, there is a considerable amount of plant in existence in the country to-day which is a potential source of trouble to the Post Office. The re-arrangement of power circuits or the laying of new Post Office lines may result in disturbances on communication circuits which may not be foreseen, and for the power engineer to provide remedies or modify existing plant might be exceedingly costly. It is very desirable, therefore, that curative methods as well as preventive methods should be devised. For this reason I suggest that these curative methods should be investigated, and a considerable amount of research work in this direction is essential. There would appear to be a wide field for the engineer who will specialize in this work and act as a liaison officer between the power engineer and the engineer who is responsible for the communication circuits.

Mr. S. C. Bartholomew *(in reply)*: As was to be expected, some of the points mentioned in the discussions in London and Liverpool have again been raised at Newcastle and Leeds in more or less the same form, and I trust my answers will be consistent.

Mr. Dalton has kindly supplied fuller details of the manner in which certain rotary converters were improved at Newcastle. I have had a word with Mr. Aldridge on the explanation advanced by Mr. Dalton for the difference in the characteristics of the harmonics in the positive and negative leads to the rotary converter, referred to in the London discussion. Mr. Aldridge points out that it is hardly likely that the difference in the alternating current in the two leads could be caused by a difference in contact resistance, as in that case there would be the same difference in the direct current carried by them. If there is a big discrepancy in the loads carried by the two cables, is not one overheated? Mr. Aldridge suggests on further consideration that the most likely cause for the difference in the ripple is as follows: Resonance conditions exist between the capacities of the generator, transformer and the positive lead and the inductance of the positive lead and part of the transformer; similarly between the capacities of the generator, transformer and negative lead, and the inductance of the negative lead, and both are excited from and in resonance with a ripple. As the capacity of the positive lead will be different from that of the negative lead the resonant frequency will be different. The negative lead, having a direct earth at the busbar, together with the rail earth, will in any case tend to reduce the resistance of the negative lead circuit and cause a greater current at the point where the test coil was placed.

I am sorry that I cannot "predict that the future will see a telephone system designed with its lines and all parts of its equipment insulated from earth." In modern telephone systems the earth is used only for signalling purposes, but very great expense and complications would result if it were not so utilized. I agree that interference would be reduced if the telegraph and telephone services were worked without earth connections, but there are limits beyond which the Administration cannot go. It must not be overlooked that but for power circuits there would be many parts of the country where single-wire telephone services would be practicable, and it can be claimed that the extra cost of the second wire has been borne by the Telephone Service without a murmur. I do not, of course, put forward the claim that single-wire telephone circuits would be satisfactory for general use in towns even if there were no power circuits, but undoubtedly the latter have absolutely prohibited their use in certain districts where single-wire working would have been possible.

Mr. Dalton raises an interesting point in connection with the publication of information that rotary converters were likely to cause interference, and suggests that earlier publication would have been a warning to purchasers and designers. When trouble was first experienced it was confined to machines made by one company, and it would have been a very questionable proceeding indeed for a Government department to have called public attention to such a failing. As stated in the paper, later experience showed that other makes of machines were equally offensive in this respect. Some publicity was given to the matter, however, in a paper read before the Institution of Post Office Electrical Engineers and reproduced fairly fully in the technical Press in January 1915. It is agreed that a considerable period elapsed between the time the converters were brought into use at Newcastle and when attention was called to the interference. Many factors contributed to this. No notification is given when there is a change in the methods of generation or distribution of energy, and the local telephone staff would naturally not associate the disturbance with the tramway system which had been in operation for so many years without causing trouble. War conditions produced staff difficulties which had a great deal to do with the toleration of unsatisfactory services for a certain period before the origin of the trouble was traced. Mr. Dalton's remarks on electrolysis and the proper layout of tramway systems to avoid its effects are of great interest. This question is not a dead one in view of the great increase in the use of lead-covered cable.

Mr. Baldwin calls attention to the certain great development of the telephone system and the power systems in this country, and as a consequence the growing importance of the matter under discussion. This is now recognized universally. Whilst I agree

that some of the functions exercised by the Co-ordinating Committees in the United States, such as the notification of prospective routes for new circuits, etc., are covered in this country by the statutory obligations of electricity undertakings to notify parties concerned of the installation of new power lines, there are other functions involving research work dealt with by the Committees which have, so far, only been lightly touched upon here.

I have already dealt with the matter of interference with broadcasting. Briefly there are three kinds of interference. The first and least troublesome is that caused to receiving sets in the neighbourhood of tramways and electric railways. So far as I can gather, these cases are not numerous. Secondly, interference with land lines used for connecting up the various transmitting and relay stations for simultaneous broadcasting. This type of disturbance may affect, in certain cases, practically the whole of the listeners in the United Kingdom. Lastly there is the interference which may affect the listeners over a wide area in the neighbourhood of works employing the Cottrell precipitators and Lempke rectifiers used for depositing blast-furnace gases. High-frequency radiation of oscillations of a broadcast wave-length may be set up and trouble has been caused here and in America on that account. A cure has been found by increasing the natural wave-length of the system by installing suitable inductances in the line. The Inductive Co-ordination Committee of the National Electric Light Association (America) has appointed a sub-committee to deal with interference of power circuits with radio or wireless reception. The purposes of the Committee are (*a*) to serve as a clearing house for information on the subject, (*b*) to conduct or supervise experimental work upon the location of sources of interference, and (*c*) to furnish the necessary information to the public.

As Mr. Whillis points out, it is sometimes found necessary where long routes are concerned to supplement the twist system of transposition by crosses. Mr. Whillis inquires as to whether cases have occurred of dangerously high voltages being induced in neighbouring telephone circuits. Since the preparation of the paper I have obtained further information and experience on this question. At the recent International Conference on Long-Distance Telephone Lines held in Paris, when the subject of power circuit interference was under discussion, particulars were given of two cases where telephone linemen at work on open lines had been electrocuted by the inductive effects brought about by faults on neighbouring power lines. In one of the cases the telephone lineman was killed in Italy whilst the actual power circuit which was faulty and produced the inductive effects was situate in Switzerland, the connecting medium being a telephone line passing through the two countries! The other case occurred in France. There have been cases in this country where telephone operators have received electric shocks in a mild form. These happenings have an important bearing on the question of earthing the neutral point on three-phase systems, as it is the unearthed system which is more likely to produce dangerous effects of this character. This is due to the fact that with the neutral point unearthed the occurrence of a fault on one phase does not operate the circuit breaker and in the event of one of the other phases making earth also at a distant point very severe disturbances are set up by the strong out-of-balance current passing between the two faults.

Mr. Gregory calls attention to the advisability of looking to the future in view of the anticipated growth in extent and design of both power and telephone systems. The automatic telephone system when operating under speaking conditions does not differ from the modern manual system as both types use common battery working of a similar character. The earth is used in connection with dialling in some cases between exchanges but, as pointed out in my reply to Mr. Cornfoot (see vol. 62, page 76) in the Liverpool discussion, from experiments made in London it is not anticipated that false signalling owing to leakage currents will be a serious matter. Unless these conditions tend to get worse, special precautions do not appear to be necessary.

Mr. Kitchen's reference to the development of long-distance telephony in Europe is *à propos*. The subject of power circuit interference is one of the principal matters being considered at the moment by the International Conference dealing with the question of long-distance telephony, and recommendations drawn up by a sub-committee recently sitting in Paris will be submitted to a full Conference to be held in the same city in the early part of June next. It is possible that modifications will be made to the recommendations at the full Conference, and the moment is not opportune for going into the proposals in detail. It is interesting to note that at some of the meetings of the sub-committee dealing with this question of power circuit interference, representatives were present from the Union Internationale des Chemins de Fer, and from the Conference Internationale des Grands Réseaux Electriques à très Haute Tension: these representatives of the electric railway and power interests were present on the invitation of the International Telephone Conference and took part in the discussion on the proposed recommendations governing the operations of the two parties. An attempt has been made to lay down minimum conditions as regards separating distance, design of plant, etc., which will ensure that there shall be no excessive interference with speech or danger to telephone plant or personnel in any of the countries concerned.

I very much appreciate the contribution from Mr. French which gives detailed information on the development of harmonics in generating plant and supplements in a most valuable manner the paper and the references in the bibliography.

The two cases of trouble instanced by Mr. Hammond are very illuminating, the case of interference at a joint pole where the angle of crossing was 60° being particularly so. It has been laid down that at this and similar types of crossing, i.e. where both the power line and the telephones are overhead, the angle of crossing should be 90°, and the need for this has frequently been challenged. Both on grounds of safety and interference, the right-angled crossing is to be preferred. The other case is a further example of interference being felt on circuits not directly con-

nected with the seat of the disturbance, the trouble being carried up by the secondary effects from intermediate circuits. To trace the origin of such trouble is very difficult, especially in cases where the disturbance is produced by one particular machine which may not be in use continuously.

Mr. Skinner asks my opinion as to the use of drainage coils on telephone circuits for the purpose of cutting down to a reasonable value the potential to earth. Apart from experiments I have had no experience of such coils on public telephone circuits. These coils offer a low-impedance path for currents induced between the telephone wires and earth, and so tend to reduce the voltage. They are no doubt very necessary on telephone circuits used in connection with the operation of power systems where the wires are in fairly close proximity to the overhead high-pressure lines, but so far their use on public telephone lines has not been found to be necessary and it is to be hoped that the conditions will not arise that will require their use on such circuits. In America the coils are called "bleeding" coils and I gather that in some cases they have been fitted on the public telephone circuits. The reduction of the voltage between the telephone wires and earth will in certain cases reduce the disturbing noise if the noise is due to this voltage acting upon a line balanced as regards insulation and capacity; on the other hand the coils will offer a low-impedance path for induced currents and if there are irregularities in the series resistance or impedance of the telephone wires the noise may be increased. Further, they must be very well balanced or they will be the cause of noise themselves by introducing unbalance into the circuit, and in addition they result in speech transmission losses. I do not think that the transposition of power lines would add very greatly to the difficulties of operation.

In reply to Mr. Mayman, I am of opinion that if the slot harmonic were removed or reduced the rising note from the motor on the car would also be reduced. I have not so far had experience of cases where it has been necessary to take special steps to reduce the latter.

In view of the possibility that the extension of power plant may be a source of trouble in the future as conditions change, Mr. Townley lays stress on the need for developing curative as well as preventive measures. Any research work in this connection would be very helpful and Mr. Townley will, no doubt, be pleased to hear that a committee of the British Electrical and Allied Industries Research Association is now looking into the whole subject.

A NEW METHOD OF HIGH-FREQUENCY RESISTANCE MEASUREMENT.

By Professor E. MALLETT, M.Sc., Member, and A. D. BLUMLEIN, B.Sc., Student.

(*Paper first received 29th September, and in final form 5th November,* 1924; *read before the* WIRELESS SECTION *7th January,* 1925.)

SUMMARY.

The paper deals with a new method of high-frequency resistance measurement involving the application of a circle diagram to a resonance curve. Various methods of measurement are evolved and experimental results are given. The application to the accurate determination of wave-length is suggested.

TABLE OF CONTENTS.

1. INTRODUCTION.

A method of high-frequency resistance measurement is developed in which the resistance of an oscillatory circuit is measured at resonance without any electrical connections being made to it. The circuit, the resistance of which is to be measured, is coupled magnetically with a coil, and the magnitude of the ratio of the effective impedance of the coil to that of the coil alone is measured at various points as resonance of the circuit is passed through by alteration of the frequency of the supply. A resonance curve of the impedance ratio is plotted against the supply frequency, and from this curve the high-frequency resistance of the circuit is determined by the use of a graphical construction involving a circle diagram. The construction gives also the value of the resonant frequency of the circuit.

Alternatively, if the tuning of the oscillatory circuit can be varied by means of a variable condenser, the impedance ratio curve can be obtained without variation of the supply frequency.

2. THEORY, SHAPE OF CURVE, AND CONSTRUCTION.

In a previous paper * a method was described of using a resonance curve of the type shown in Fig. 1 to obtain the natural frequency and the decay factor of a telephone diaphragm. To effect this a geometrical construction was evolved and the same construction and method were shown to be applicable to coupled circuits.

For the sake of completeness the theory may be briefly restated. Consider a coil of impedance Z_1 (see Fig. 2) coupled magnetically to a resonant circuit of impedance Z_2. Let M be the mutual inductance and V the alternating voltage applied to the terminals of the first coil, which will be called the coupling coil.

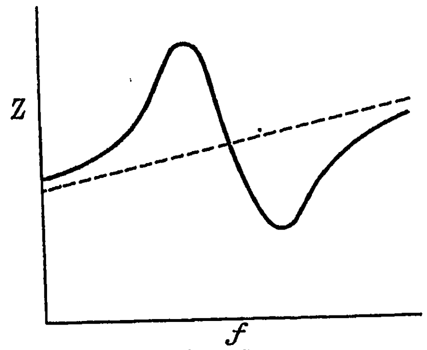

FIG. 1.

Then if I_1 and I_2 are the currents in the first and second circuits respectively:—

$$V = Z_1 I_1 + j\omega M I_2 \quad . \quad . \quad . \quad . \quad (1)$$

$$0 = Z_2 I_2 + j\omega M I_1 \quad . \quad . \quad . \quad . \quad (2)$$

From (2) we obtain:—

$$I_2 = -j\frac{\omega M}{Z_2} I_1$$

Putting this value of I_2 in (1) we get:—

$$V = Z_1 I_1 + \frac{\omega^2 M^2}{Z_2} I_1$$

The effective impedance Z is V/I_1, and

$$Z = \frac{V}{I_1} = Z_1 + \omega^2 M^2 \frac{1}{Z_2}$$

Taking the ratio Z/Z_1 we get:—

$$\frac{Z}{Z_1} = 1 + \frac{\omega^2 M^2}{Z_1} \cdot \frac{1}{Z_2} \quad . \quad . \quad . \quad . \quad (3)$$

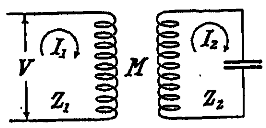

FIG. 2.

No account has been taken of the self-capacity of the coupling coil, and therefore to make the theory applicable it is essential that the coupling coil should have a natural frequency well above the natural frequency

* E. MALLETT: *Journal I.E.E.*, 1924, vol. 62, p. 517.

of the circuit to be tested, i.e. well above the frequencies * used in the tests.

In Fig. 3 is given the vector interpretation of Equation (3). If in the arrangement of Fig. 2 the supply frequency were increased from below to above the resonant frequency of the second circuit, the locus of the end of the vector OP representing Z_2 would move upwards along a straight line PQ. The end of the vector OP′ representing $1/Z_2$ would then move round the circle OP′Q′ in a clockwise direction, starting from the origin. The diameter OR of the circle is $1/R_2$. This circle is the inverse of the previous straight line, and the line OP′ corresponds to the line OP where $\angle$ P′OX $= \angle$ POX.

For small changes of frequency, if Z_1 is far removed from resonance ω^2M^2/Z_1 will be proportional to ω and will not alter appreciably in magnitude or phase angle, and the locus of the vector $(\omega^2M^2/Z_1)(1/Z_2)$ will be obtained by turning the circle through the angle of $1/Z_1$ and multiplying its diameter by $|\omega^2M^2/Z_1|$. This operation gives the circle OP″Q″ with a diameter OD at an angle XOD = the angle of Z_1. Marking

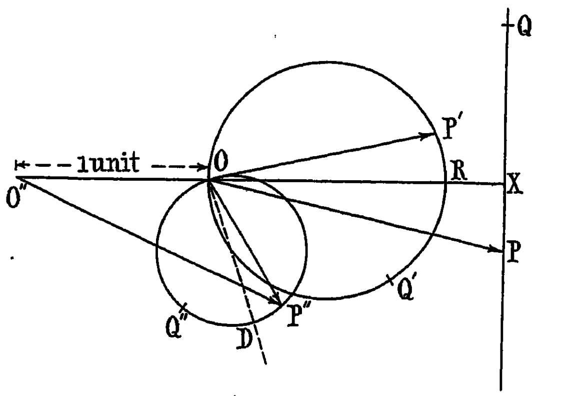

Fig. 3.

off OO″ horizontally equal to unity, any vector O″P″ is evidently equal to the vector sum of 1 and $(\omega^2M^2/Z_1)(1/Z_2)$ and so is equal to Z/Z_1.

The maximum and minimum values of Z/Z_1 can be found by drawing a line from O″ passing through the centre of the circle OP″Q″. The points at which this line cuts the circle then give the maximum and minimum values of Z/Z_1. Conversely, knowing the maximum and minimum values of Z/Z_1, by a suitable construction the circle can be drawn.

Consider a curve of Z/Z_1 plotted against f as in Fig. 4. By drawing lines parallel to the f axis touching the curve at its maximum and minimum points, two vertical distances ON and OM are marked off equal to the maximum and minimum values of Z/Z_1. Then with centre O and radii OM and ON arcs are drawn, and finally a circle is drawn to touch these two arcs and to pass through the point A, such that OA = 1. Take any point P on the circle and draw OP. Then OP represents Z/Z_1 in magnitude and phase. A and O in Fig. 4 correspond respectively to 0 and 0″ in Fig. 3.

As the frequency increases from a low to a high value the end of the vector OP moves round the circle in a clockwise direction from A back to A. This is not strictly true as the value of ω^2M^2/Z_1 varies, but for small changes of frequency close to resonance this is applicable, and with the circuits commonly used in wireless most of the circle is described with a very small frequency-change.

To find the frequency corresponding to any point P, on the locus circle, an arc is drawn with centre O through P to meet the Z/Z_1 axis in L, and then a line drawn through L parallel to the f axis to meet the curve in P′, the point on the resonance curve corresponding to the point P on the circle.

There is an ambiguity in finding P′, as according to the construction the horizontal line cuts the curve in two points; but this ambiguity is removed when it is remembered that, as the circle is described clockwise from A, the resonance curve is drawn to the right from A′.

The vector AP represents in magnitude and phase $(\omega^2M^2/Z_1)(1/Z_2)$. At resonance $1/Z_2 = 1/R_2$ and AP lies on the circle diameter AD, the angle of which is the angle of ω^2M^2/Z_1. If therefore A is considered as the origin and the diameter AD as the line of refer-

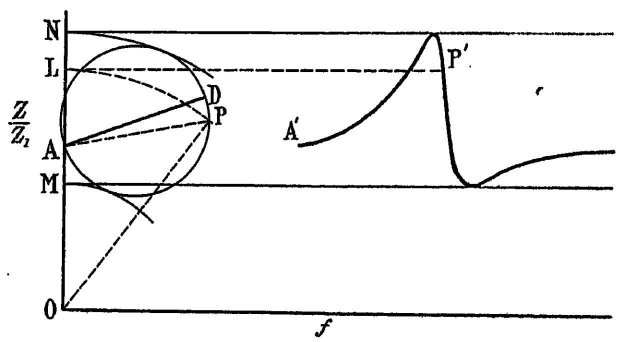

Fig. 4.

ence, AP then represents the vector $|\omega^2M^2/Z_1|(1/Z_2)$; and since ω^2M^2/Z_1 is now a magnitude, AP represents to some other scale the vector $1/Z_2$. The angle PAD is then the phase angle of $1/Z_2$.

Call this angle PAD α, the phase angle of Z_2, or − (the phase angle of $1/Z_2$).

Then

$$\tan\alpha = \frac{\omega L_2 - 1/(\omega C_2)}{R_2}$$

where L_2, C_2 and R_2 are respectively the inductance, capacity and resistance of which Z_2 is composed.

Let
$$\omega_0 = \frac{1}{\sqrt{(L_2C_2)}}$$

Then
$$\begin{aligned}\tan\alpha &= \frac{\omega L_2 - 1/(\omega C_2)}{R_2}\\ &= \frac{L_2}{R_2}\left(\omega - \frac{1}{\omega L_2 C_2}\right)\\ &= \frac{L_2}{R_2}\left(\omega - \frac{\omega_0^2}{\omega}\right)\end{aligned}$$

* See Appendix 2.

Differentiating with respect to ω, we obtain :—

$$\frac{d \tan \alpha}{d\omega} = \frac{L_2}{R_2}\left(1 + \frac{\omega_0^2}{\omega^2}\right)$$

For values of ω close to resonance we have $\omega_0 \doteqdot \omega$

so that $$\frac{\omega_0^2}{\omega^2} \doteqdot 1$$

$$\therefore \quad \frac{d \tan \alpha}{d\omega} = \frac{2L_2}{R_2}$$

and $\dfrac{d\omega}{d \tan \alpha} = \dfrac{R_2}{2L_2} = \Delta$, the decay factor.

Now for any point P on the resonance curve (see Fig. 4) the corresponding point on the circle can be found, and hence tan α which equals tan PAD. By repeating this process for other points on the curve, the values of tan α corresponding to various values of ω are obtained, and a curve of tan α against ω can be drawn. For small changes of ω this curve will be a straight line. The value of ω at which tan $\alpha = 0$ gives the resonant frequency, and the slope $d\omega/(d \tan \alpha)$

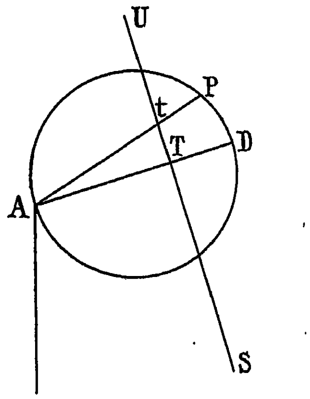

FIG. 5.

of the straight-line portion of the curve $= \Delta$, the decay factor of the circuit.

This gives $R_2/(2L_2)$, and, if we know the value of L_2, we can find R_2 the resistance required.

Instead of measuring off the angles α and finding their tangents from tables, the ω — tan α curve may be obtained graphically. A line STU (see Fig. 5) is drawn at right angles to the diameter AD of the circle at a distance AT equal to unity to some suitable scale. Then the tangent of the angle α of any vector AP is obviously given to the same scale by the length Tt and is negative above T and positive below T. This length is then marked off from a suitable base line drawn for convenience below the original resonance curve so that the same frequency scale is used for the new ω — tan α curve.

Approximate construction.—A simplified construction can be employed when the variation of Z/Z_1 is small compared with unity.

In Fig. 6 is shown a typical Z/Z_1 curve. As before, lines are drawn parallel to the ω axis through the maximum and minimum points to N and M. As the variation of Z/Z_1 is small the origin will be a long way away, and so arcs drawn with O as centre through N and M will, for a short length, be practically parallel to the ω axis.

The circle can therefore be drawn between the parallels M and N. Any point P′ will have its corresponding point on the circle found by drawing PP′ parallel to the ω axis to meet the circle in P.

As before, tan α is plotted against ω and the slope of the line gives Δ.

This construction can only be used when the variation of Z/Z_1 is small. By a method of trial and error it has been found that the approximate construction can be applied to curves with a variation of Z/Z_1 less than 0·2. For example, if a curve has maximum and minimum values of $Z/Z_1 = 1{\cdot}07$ and 0·92 the variation of Z/Z_1 is 0·15 and the approximate construction may be used.

Method employing constant frequency and variable tuning of the circuit under test.—For circuits that are tuned by a variable condenser a modification is applicable, in which ω is kept constant and ω_0 is varied by varying the capacity in the circuit under test. ω^2M^2/Z_1 will then be constant and, as before,

$$\Delta = \frac{d\omega_0}{d \tan \alpha}$$

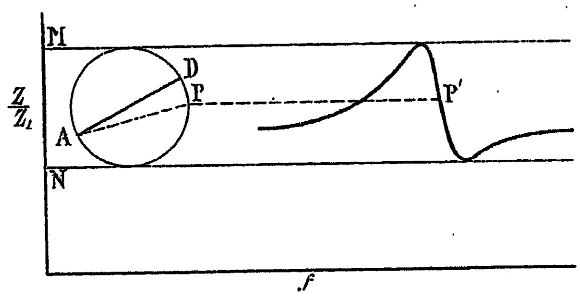

FIG. 6.

Z/Z_1 is plotted against ω_0 instead of ω and the construction is the same as before.

The essential points therefore based on these considerations are briefly as follows :—

The determination of high-frequency resistance.—(*a*) Measurements of the magnitude of the apparent impedance of the coupling coil are taken for various values of ω,

(i) With circuit to be tested magnetically coupled to the coupling coil (this gives Z) ; and
(ii) Without the circuit to be tested (this gives Z_1).

(*b*) A curve of Z/Z_1 is plotted against ω.

(*c*) The locus circle, as determined from the maximum and minimum values of Z/Z_1, is drawn.

(*d*) A curve of tan α against ω is plotted and a straight line drawn through the points obtained.

(*e*) The slope $d\omega/(d \tan \alpha)$ of this line is measured and is equal to Δ, the decay factor of the circuit to be tested ; hence the desired resistance is determined.

(*f*) The value of ω when tan $\alpha = 0$ is the resonance value.

3. Various Methods of Measurement.

It is evident from the above that the determination of the decay factor depends upon the accurate measurement of (i) frequency-changes and (ii) impedance ratios.

A circuit diagram of the whole of the apparatus finally used in the "Voltmeter method" is given in Fig. 7, but the oscillator and amplifier arrangement to the right of the diagram was used finally in each method. This consists, it will be seen, of a small oscillating valve supplying an E.M.F. to an amplifying valve, from which the necessary current for the impedance measurement was obtained. In this way, by using a negative grid on the amplifying valve no external load is placed on the oscillating valve, so that circuit changes taking place beyond the amplifying valve do not have any effect on the frequency of the oscillating valve. The usual precautions were taken to obtain as pure a wave-form as possible. The oscillating valve was only just maintained, and it was worked with sufficiently high anode potential and negative grid bias to prevent grid current flowing. Careful adjustments were made so that the anode current as measured on a d.c. instrument was the same when oscillating as when not oscillating. The same adjustment was made on the amplifying valve, and care was taken that the a.c. grid potential supplied from the oscillator was never sufficient to cause the amplifying valve to work on the curved portions of its characteristic.

Table 1.

750-turn Igranic coil (9 000 *m*).

Condenser reading	Z		Z_1			$\frac{Z}{Z_1}$
	R_a	R_v	R_a	R_v	Z_1	
10	13·0	54	13·0	66	21·32	0·956
15	13·0	53	—	—	21·49	0·949
20	13·0	51	—	—	21·65	0·911
25	13·0	50	13·0	65	21·81	0·898
30	13·0	49	—	—	21·98	0·883
35	12·9	48	—	—	22·14	0·863
40	12·8	46	13·0	64	22·30	0·85
45	12·7	46	—	—	22·46	0·847
50	12·3	48	—	—	22·63	0·873
55	11·8	56	13·0	67	22·79	0·955
60	11·3	74	—	—	22·95	1·115
65	11·5	96	—	—	23·11	1·248
70	12·0	103	13·1	71	23·28	1·257
75	12·7	101·5	—	—	23·44	1·208
80	12·9	97	—	—	23·60	1·156
85	13·1	94	13·3	75	23·76	1·127
90	13·2	92	—	—	23·92	1·102
95	13·1	91	—	—	24·09	1·092
100	13·1	90	13·3	79	24·25	1·079
105	13·2	89	—	—	24·42	1·062
115	13·3	89	13·3	81	24·74	1·045
125	13·3	89	13·3	81	25·06	1·031

In order to make the frequency-changes as easily determined as possible, the oscillatory circuit of the oscillator valve was made up for a given frequency with as large a capacity and as small an inductance as possible, and the very small frequency-changes required were effected by means of vernier condensers, and were in most cases very nearly simply proportional to the alteration of the vernier capacity, as is shown in Section 5.

(*a*) *Voltmeter-ammeter method.*—The obvious way of measuring the magnitude of the impedance of a network at any frequency is to pass a current of that frequency through the network and to measure both the current and the voltage across the network, and this was the first way in which results were obtained. The current was obtained from the amplifier valve through a transformer or large condenser across an anode resistance so as to separate out the d.c. anode current. The current was measured by a Duddell thermo-milliammeter, and the voltage by one of Prof. Mather's sensitive electrostatic instruments. Since the voltage was measured over both the coupling coil and the milliammeter, Z_1 of the formula included the resistance of the latter.

The first series of measurements was made on a 750-turn "duolateral" coil, tuned with a variable air-condenser, at a frequency corresponding to about 9 000 m. The coil had an inductance of 31 900 μH and a self-capacity at this wave-length of about 22 $\mu\mu$F. The resistance of the coil and condenser was found to be of the order of 100 ohms at this frequency.

One series of readings is given in Table 1. Both the milliammeter and the voltmeter were square-law instruments and the impedance was calculated as $\sqrt{(R_v/R_a)}$, where R_v and R_a were the ammeter and voltmeter readings respectively. Only a few readings were taken for Z_1, and the rest were interpolated. The frequency was varied by varying a small condenser in the oscillator anode circuit. As the capacity in the oscillator anode circuit was large, over a small range $\omega \propto (k - C_1)$, where C_1 is the capacity of the small variable condenser. Between 10° and 170° the small condenser had a straight-line law, and so Z/Z_1 was plotted against the reading of the small condenser and the change of ω per scale division calculated. The same method has been applied in other cases where the variation of ω was small.

From the curve, $\Delta = 1\,848$; $R = 118$ ohms.

The curve obtained and the construction to find Δ are given in Fig. 8.

The slope of the $\omega - \tan\alpha$ curve is 12·2 condenser divisions per unit change of $\tan\alpha$. The change of ω per scale division of the condenser is 151·5.*

Then

$$\Delta = d\omega/(d\tan\alpha) = 12{\cdot}2 \times 151{\cdot}5 = 1\,848$$

Assuming that the high-frequency inductance is the same as its low-frequency value we have

$$R = \Delta \times 2L = 1\,848 \times 2 \times 31\,900 \times 10^{-6}$$
$$= 118 \text{ ohms.}$$

This result is not very reliable as the method did not prove at once satisfactory; and it was not developed in view of the simpler methods now to be described.

* See Section 5

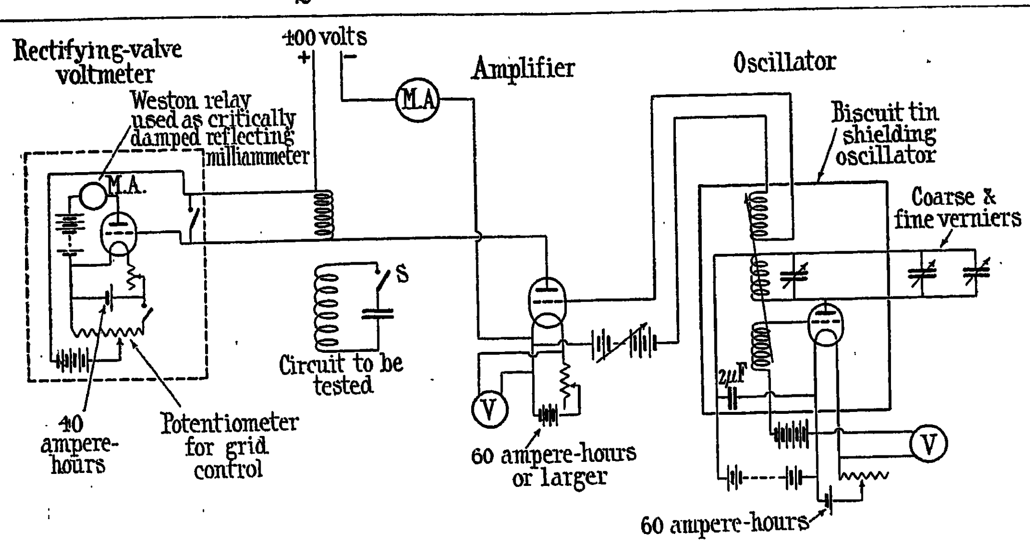
Rectifying-valve voltmeter
Weston relay used as critically damped reflecting milliammeter
M.A.
40 ampere-hours
Potentiometer for grid control
400 volts
M.A
Circuit to be tested
S
Amplifier
V
60 ampere-hours or larger
Oscillator
Biscuit tin shielding oscillator
Coarse & fine verniers
2μF
V
60 ampere-hours

FIG. 7.

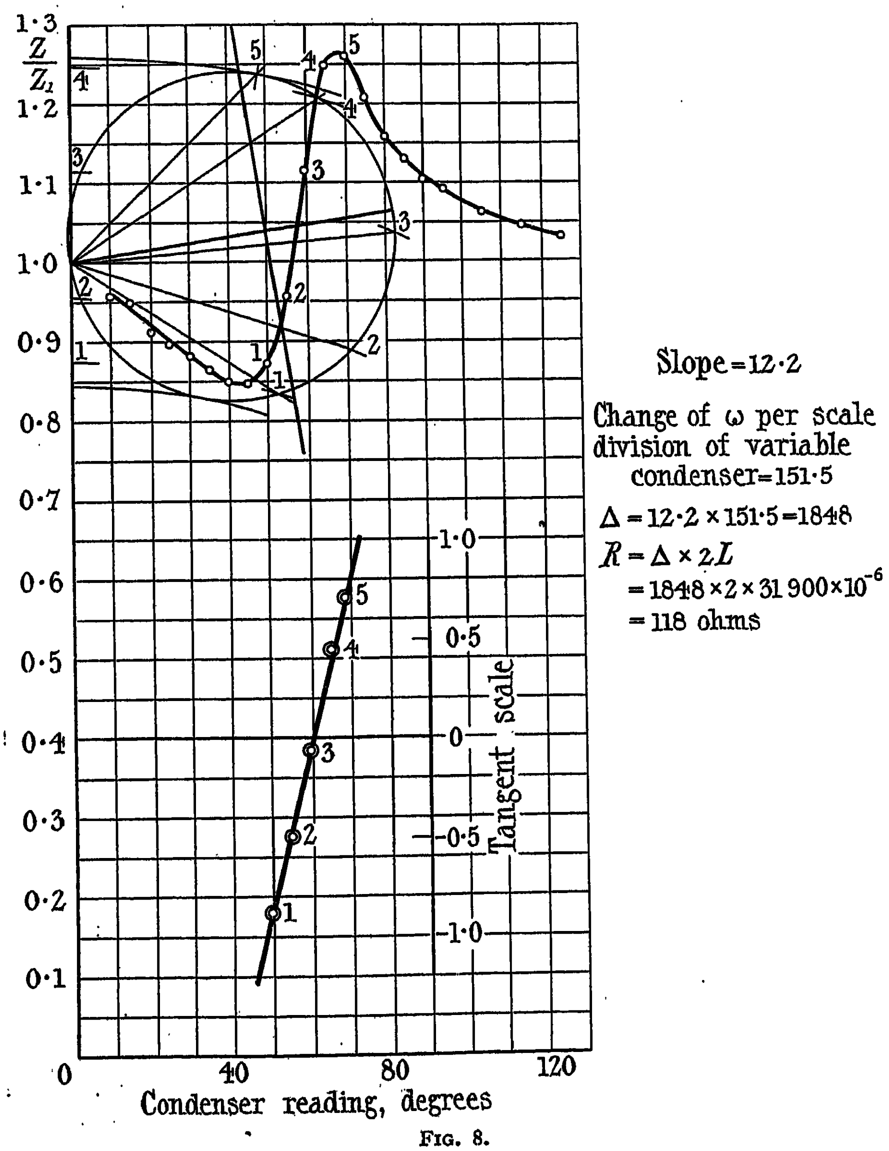
Z/Z1
1·3
1·2
1·1
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0
40
80
120
Condenser reading, degrees
Tangent scale
1·0
0·5
0
-0·5
-1·0
Slope=12·2
Change of ω per scale division of variable condenser=151·5
Δ=12·2×151·5=1848
R=Δ×2L
=1848×2×31 900×10^-6
=118 ohms

FIG. 8.

(b) *Voltmeter method.*—Since only the ratio of the impedances is required, as long as the current through the coupling coil remains constant whether the resonant circuit is coupled with it or not, the required impedance ratio will be obtained as the ratio of the voltages across the coil in the two cases. It does not matter if different currents are used at different frequencies. At first an attempt was made to keep the current constant (as indicated by a crystal and galvanometer across a series resistance) by altering the coupling between the amplifier and oscillator, but it was soon found that the oscillator was better left alone and in any case the adjustment was laborious. Then it appeared that if the whole

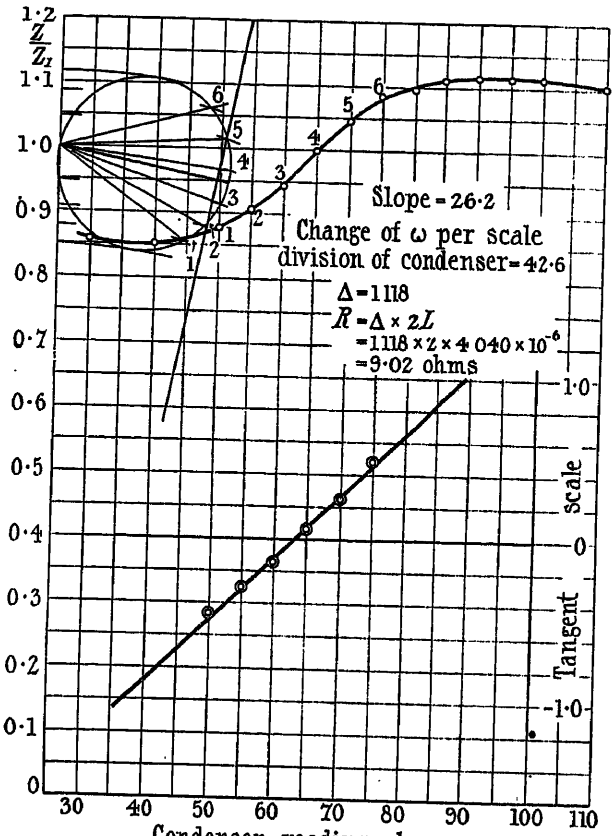

FIG 9.

impedance of the circuit containing the coupling coil was large compared with that of the coupling coil itself the current would remain sensibly constant with constant E.M.F., and that in order to obtain a sufficiently large impedance the internal resistance of the amplifying valve could be used by placing the coupling coil direct in the anode circuit.

Since the grid of the amplifier valve was very negative and no grid current flowed, the a.c. voltage E_g passed on to the grid of the amplifying valve from the oscillator was constant for any one frequency. The a.c. portion of the anode current of the amplifier valve is then

$$\frac{\mu E_g}{R_0 + Z}$$

where R_0 is the internal resistance and μ the amplification factor of the amplifier valve, and, as before, Z is the effective impedance of the coupling coil.

Provided therefore that the alterations of Z are small compared with the value of $(R_0 + Z)$, the current through the coil will not vary appreciably and we can measure Z by measuring the potential across the coupling coil; this measurement can be made by means of a calibrated rectifying valve. The small alterations of current that do take place do not affect the resistance determinations.*

TABLE 2.

4 040 μH coil at 3 800 m. No added resistance.

Condenser reading	V	V_1	Ratio $\frac{Z}{Z_1} = \frac{V_1}{V_1}$
	volts	volts	
30	1·28	1·495	0·856
40	1·27	1·49	0·852
50	1·31	1·49	0·879
55	1·35	1·49	0·906
60	1·405	1·485	0·946
65	1·475	1·475	1·000
70	1·55	1·480	1·046
75	1·60	1·475	1·085
80	1·62	1·475	1·098
85	1·64	1·475	1·112
90	1·645	1·475	1·114
95·5	1·642	1·475	1·115
100	1·64	1·47	1·115
110	1·62	1·47	1·102

Change of ω per scale division of condenser = 42·6.
From the curve Δ = 1 118; R = 9·02 ohms.

The general arrangement is shown in Fig. 7. The grid voltage of the rectifying valve could be adjusted by means of a potentiometer to allow for the d.c. voltage across the coupling coil due to the steady plate

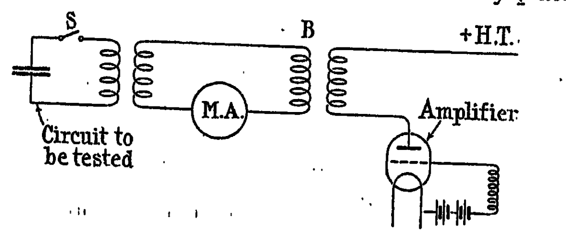

FIG. 10.

current of the amplifying valve. The rectifying valve consisted of a D.E.R. type valve working with an anode voltage of about 35 and a negative grid bias of about 4·5 volts.

The procedure was as follows:—

The potentiometer was adjusted to make the grid of the rectifying valve full negative. Then, with the amplifying valve turned off, the filament current of the rectifying valve was adjusted to give a definite predetermined anode current representing zero a.c. volts on the calibration curve. This adjustment was

† See Appendix 1.

repeated several times during a quarter of an hour to allow the rectifying valve to settle down. The amplifying valve was then turned on, and its filament voltage adjusted to the right value. This caused the anode

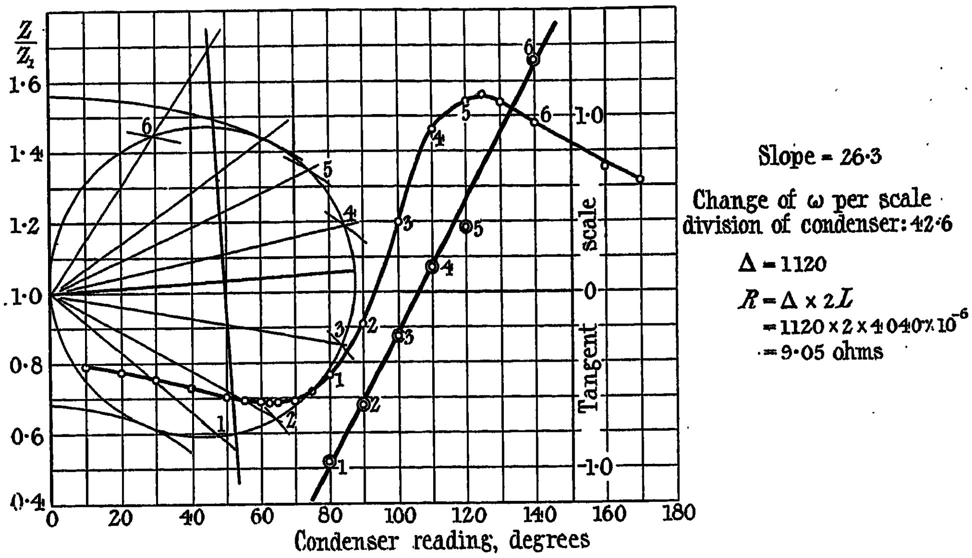

FIG. 11.

current of the rectifying valve to decrease due to the potential of its grid being reduced by the P.D. across the coupling coil. This was allowed for by adjusting the potentiometer until the anode current of the rectifying valve was again at its previous value. The oscillating valve was then turned on and readings were taken.

In the actual arrangement shown there was a very convenient method for determining Z_1. It was found that if the switch S in the circuit to be tested (see Fig. 7) is opened, the effect is the same as actually removing the resonant circuit. Therefore the order of measurements was arranged as follows:—

(i) Switch opened and V_1 measured.
(ii) Switch closed and V measured.
(iii) Switch opened and the previous value of V_1 checked.

Then

$$\frac{Z}{Z_1} = \frac{V}{V_1}$$

on the assumption that the current has not changed during the operations.

On repeating a previous reading, V and V_1 were sometimes found to have changed a little, but the ratio Z/Z_1 remained the same.

Table 2 and Fig. 9 give details of a measurement made in this way. These results are referred to again in Section 4.

(c) *Ammeter method.*—Another method has been evolved similar to the last in which a current measurement only is made. The arrangement is shown in Fig. 10. The amplifier and oscillator are arranged as before (see Fig. 7). As before, the a.c. anode current of the amplifier valve is constant for any one frequency; this gives a constant E.M.F. in the coil B. The impedance of the coil B and of the milliammeter are included in Z_1, and the effective impedance is inversely proportional to the milliammeter reading. Three readings are taken at each frequency; two with the switch open gave Z_1, and one with the switch closed gave Z. The required impedance ratio Z/Z_1 is given by I_1/I. Table 3 and Fig. 11 give results of a measurement made in this way.

TABLE 3.

4 040 μH *coil at* 3 800 *m. No added resistance.*

Condenser reading	I_1	I	Ratio $\frac{Z}{Z_1} = \frac{I_1}{I}$.
	mA	mA	
10	5·82	7·31	0·796
20	5·835	7·53	0·7745
30	5·86	7·80	0·751
40	5·885	8·00	0·7305
50	5·905	8·34	0·705
55	5·885	8·44	0·698
60	5·895	8·55	0·689
62	5·88	8·55	0·6875
65	5·89	8·56	0·6885
70	5·81	8·38	0·6935
75	5·875	8·19	0·7175
80	5·875	7·68	0·7645
90	5·895	6·47	0·911
100	5·885	4·93	1·195
110	5·86	4·01	1·462
120	5·84	3·79	1·541
130	5·83	3·79	1·539
125	5·83	3·76	1·551
140	5·83	3·95	1·476
160	5·815	4·30	1·352
170	5·82	4·43	1·314

Change of ω per scale division of condenser = 42·6.
From the curve, $\Delta = 1\,120$; $R = 9 \cdot 05$ ohms.

Of the three methods the first is the most complicated and least satisfactory for general engineering work. The ammeter method requires the simplest assemblage of apparatus but necessitates a closer coupling to the resonant circuit. Probably the voltmeter method will be the most generally useful and accurate.

4. Experimental Results.

Altering coupling and adding resistance.—The coil, the resistance of which was found by the voltmeter and by the ammeter method (Tables 2 and 3 and Figs. 9 and 11) consisted of 189 turns of No. 22 S.W.G. d.c.c. wire wound on a former 7 inches in diameter and $7\frac{1}{2}$ in. long. To reduce the dielectric losses the coil had been thoroughly "baked" with both direct and high-frequency alternating current. The inductance of the coil was 4 040 μH, its d.c. resistance 4·6 ohms and its self-capacity about 7 $\mu\mu$F. It was tuned by means of a variable air-condenser. The coupling coil was wound of finer wire on a former of smaller diameter, and had an inductance of 700 μH and a self-capacity of 10 $\mu\mu$F. The two coils were mounted so that their axes were in line and their distance apart could be readily altered.

As will be seen from Figs. 9 and 11, the resistance obtained at a frequency value corresponding to 3 800 m by the voltmeter method was 9·02 ohms and by the ammeter method 9·05 ohms. The mutual inductance between the two coils was very much greater in the second case, and the remarkably close agreement of the two determinations indicates that the degree of coupling is as it should be by the simple theory, i.e. without effect, and that each method can give equally good results. Further measurements at different couplings by the voltmeter method confirmed that the coupling was without appreciable effect, although the agreement was not quite so striking. Leaving out one determination at 8·70 ohms which was rejected as the points obtained did not lie well enough on a straight line, the difference between the greatest and least figure obtained at different times and different couplings was just over 1 per cent.

As a check measurement a fine eureka wire resistance was added to the oscillatory circuit with the coupling coil in the same position as that used in Fig. 9, with the results given in Fig. 12. The high-frequency resistance of the circuit was now measured as 17·30 ohms, a difference of 8·28 ohms from the determination of 9·02 ohms without the added resistance. The actual value of the added resistance was 8·38 ohms, so that the actually measured resistance of the wire at high frequency was only about $1\frac{1}{4}$ per cent in error. It must be added here that some other determinations in the same way did not check up nearly so well, although the points obtained for the Δ — tan α curves lay on straight lines. The difficulties in adding resistance to the circuit seem to be similar to those encountered in the substitution or added-resistance method of high-frequency resistance measurement. It would appear to be quite possible that the high-frequency resistance measurements here described are more accurate than their check by adding resistance.

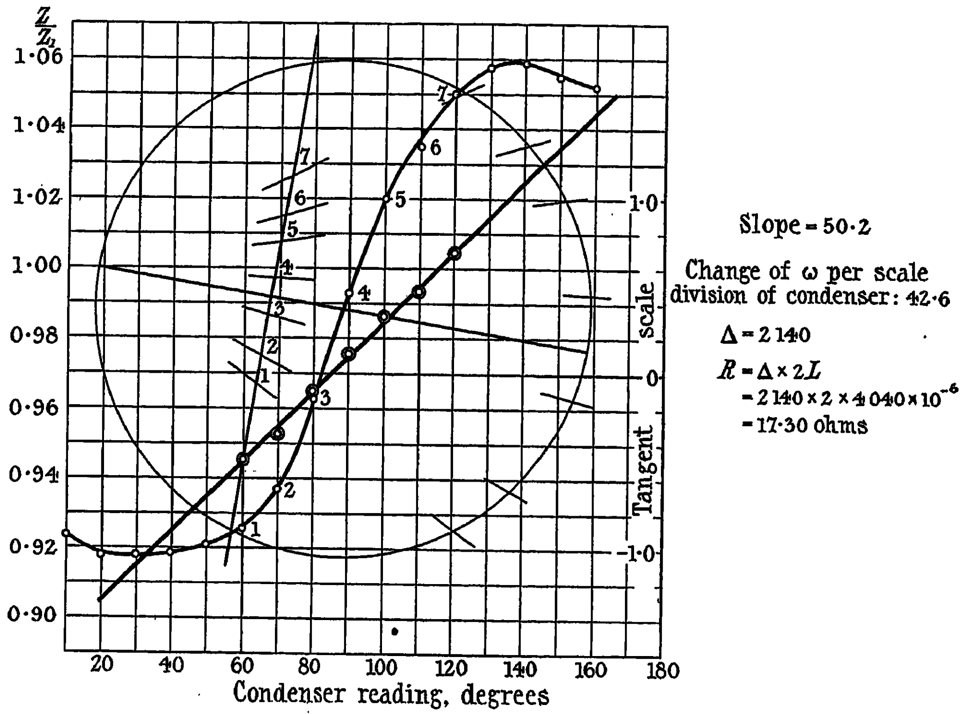

Fig. 12.

Measurements have been made over a considerable frequency range and with coils of very different resistances. Some of the results are given below.

50 ohms at 500 metres.—A series of measurements

was made on a small "reaction coupling coil" from a broadcast receiving set, and consisting of two coils wound on an ebonite bobbin, with the ends brought out to four pins arranged to fit a valve socket.

The resistance of the larger of the two coils was measured at 500 m. This coil had an inductance of 284·7 μH and its resistance was found to be about 50 ohms. Measurements were taken by varying both ω and ω_0. The results of the latter measurement are given in Fig. 13 as an example of the results obtained in this way.

In these cases the variations of ω were too large for it to be permissible to plot the ratio Z/Z_1 against the reading of the vernier condenser in the oscillator experienced due to "feed back" through the inter-electrode capacity of the amplifier valve. This was avoided by making the amplifier coupling coil (coupled to the oscillator) an effective capacity, i.e. using a coil working well above its natural frequency.* This prevents any regenerative feed-back taking place.

The results were :—

Varying ω : resistance = 46·3 ohms.
Varying ω_0 : resistance = 44·6 ohms.

The difference is 3·8 per cent. The results are sufficiently close to show that the two methods agree; the first measurement was not particularly good as judged by the straight line.

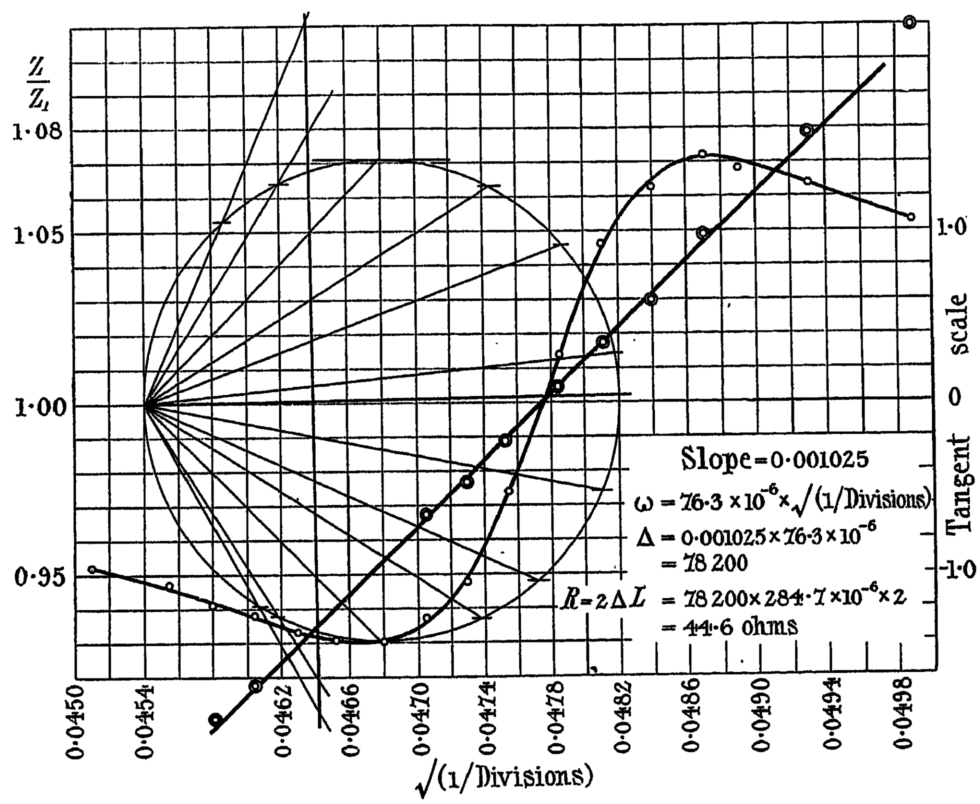

FIG. 13.

anode circuit. From the known wave-length and inductance of the oscillator anode coil, the effective capacity in parallel with it could be calculated. This was expressed in scale divisions of the vernier condenser. We then get :—

$$\omega = \frac{1}{\sqrt{(LC)}} = \frac{1}{\sqrt{[Lk(\text{scale divisions})]}} = K\frac{1}{\sqrt{(\text{divisions})}}$$

where total capacity $C = k$ (scale divisions of vernier condenser).

Z/Z_1 is therefore plotted against $1/\sqrt{(\text{divisions})}$ and the value of K calculated. This saves considerable time in calculating the results. The same method has been applied when plotting against ω_0.

While taking these measurements, trouble was

80 and 8 *ohms at* 300 *metres*.—Two more measurements were made on the same "reaction coupling coil"; the resistance of both coils was found at 300 m. The results obtained with the small coil are given in Fig. 14, as they bring out an interesting point (see Appendix 2).

The figures are :—

Large coil.
Inductance = 284·7 μH.
Resistance = 78·7 ohms.

Small coil.
Inductance = 23 μH.
Resistance = 7·75 ohms.

Taking into consideration the high frequency used,

* See A. S. BLATTERMAN: *Radio Review*, 1920, vol. 1, p. 633.

these results are not altogether unsatisfactory. No special precautions were taken to avoid stray resonances or capacities, and the oscillator and amplifier shared common and not too large filament batteries. (The measurements were made before the apparatus of Fig. 7 was assembled.) The large coil gave better results and the points lie on quite a good straight line. Though the curve is not good for the small coil, the points define the straight line within 2 or 3 per cent.

It is interesting to notice that the ratio of the resistances of the large coil at 300 and 500 m is $78 \cdot 7/45 \cdot 5 = 1 \cdot 73$, and the ratio of the frequencies is $1 \cdot 67$.

5 ohms at 500 metres.—The resistance of a toroidal coil of inductance 158 μH and resistance about 5 ohms was measured at 500 m. Mutual coupling was obtained by linking two turns of wire through the toroid and supporting them from an insulator. These two turns were put in series with a small coil so as to bring the combined inductance up to such a value that a P.D. to be measured of about $1 \cdot 3$ volts was obtainable, as the voltmeter in use was most sensitive for voltages round about $1 \cdot 3$. Z_1 then consisted of the two coupling turns and the small coil in series with them.

The variation of $Z/Z_1 = 1 \cdot 117 - 0 \cdot 912 = 0 \cdot 205$; this is just above the limit below which it is permissible to use the approximate construction. Both the rigid and the approximate constructions have been drawn and give practically identical figures of $4 \cdot 68$ ohms.

5. Frequency Determinations.

The resonant frequency of the oscillatory circuit is found from the $\omega/\tan \alpha$ line where it cuts the tan α axis, and a determination of resonant frequency made in this way is capable of considerable accuracy.

A very close approximation with the circuits in general use in wireless work is obtained by taking the resonant frequency as being that at which the impedance of the coupling coil with the oscillatory circuit open is the same as that with the oscillatory circuit closed, with the additional condition, of course, that the observation is made at the central portion of the curve where the impedance is changing rapidly with frequency. This fact was used to check the assumption made throughout that the change of frequency was determined by the change of the vernier condenser of the oscillator, and to find the $\delta\omega - \delta C$ calibration of the oscillator.

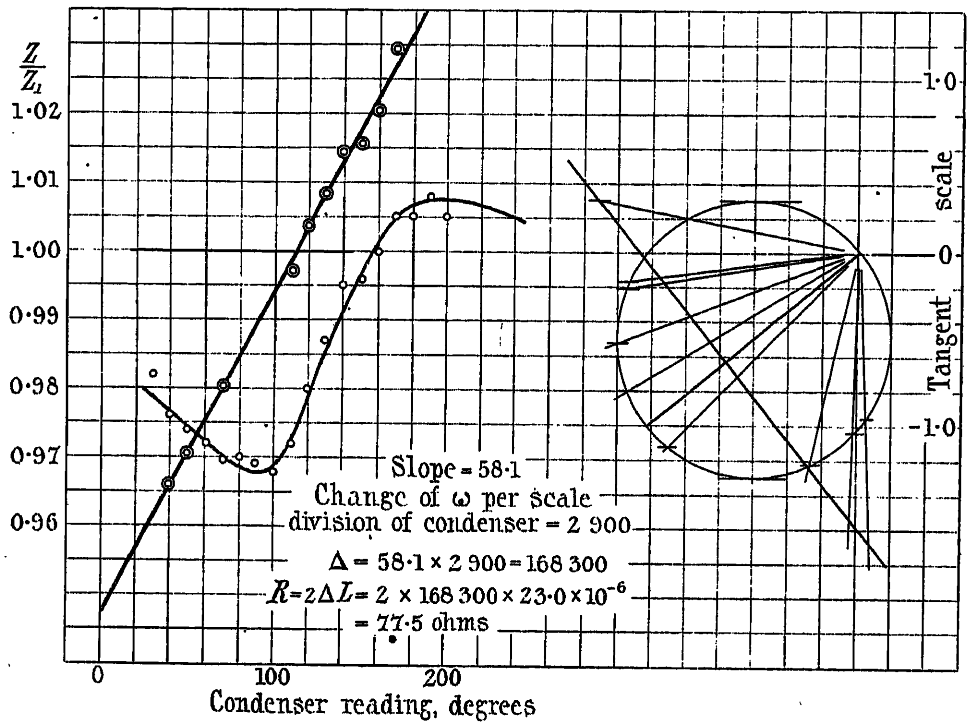

Fig. 14.

With the apparatus set up as in Fig. 7 and the oscillator condensers adjusted for resonance of the oscillatory circuit as determined by the open-circuit voltmeter reading being the same as the closed-circuit reading, the smaller of the two oscillator vernier condensers was removed and the remaining one adjusted to restore the oscillator to its original frequency, this being done by bringing the voltmeter reading back to its original value (on the central part of the curve). This smaller condenser C_2 was then put in parallel with the oscillatory circuit condenser C (see Fig. 15) and the latter reduced until the reading of the voltmeter was again the same. The value of the remaining oscillator vernier C_1 was now altered a little, and C_2 adjusted until the closed-circuit voltmeter reading was the same as the open-circuit reading, that is until the oscillatory circuit was again very nearly tuned to the oscillator. The corre-

sponding readings of the condensers are given in Table 4 and plotted in Fig. 16.

The fact that these points lie on a straight line justifies the assumption made.

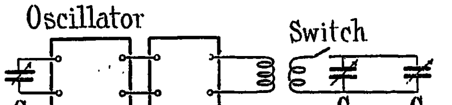

FIG. 15.

Calibration of the verniers gave for the straight-line part of the calibration curve :—

$$C_1 \quad .. \quad \delta C_1 = 6 \cdot 57 \ \delta\theta_1 \ \mu\mu F$$
$$C_2 \quad .. \quad \delta C_2 = 0 \cdot 638 \ \delta\theta_2 \ \mu\mu F$$

where θ_1, θ_2 are the readings in degrees.

TABLE 4.

θ_1	θ_2
150	143
140	116
130	89
120	61
110	33

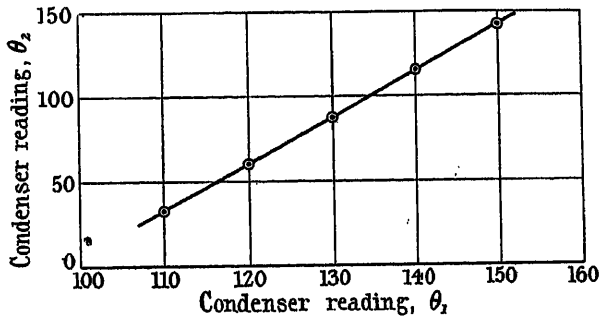

FIG. 16.

With C_2 at 20°, the capacity of C and C_2 together measured 998 $\mu\mu$F; the inductance of the coil was 4 040 μH and its self-capacity 7 $\mu\mu$F. Its ω_0 is accordingly

$$\frac{1}{\sqrt{(LC)}} = \frac{10^9}{\sqrt{(4\,040 \times 1\,005)}}$$
$$= 0 \cdot 495 \times 10^6$$

corresponding to a wave-length of 3 810 m. This was checked by a heterodyne wave-meter.

$$\text{Since } \omega = \frac{1}{\sqrt{[L(C + \delta C)]}} = \omega_0\left(1 - \frac{\delta C}{2C}\right)$$

$$\delta\omega = -\frac{\omega_0}{2C}\delta C$$

$$= -\frac{0 \cdot 495 \times 10^6}{2 \times 1\,005} \times 0 \cdot 638 \ \delta\theta_2 = 157 \cdot 1 \ \delta\theta_2$$

as determined from the oscillatory circuit.

The slope of the line of Fig. 16 is

$$\frac{d\theta_2}{d\theta_1} = 2 \cdot 79$$

so that a change of reading of C_2 corresponds to $2 \cdot 79$ times the change of C_1. $\delta\omega$ therefore, calculated from the oscillator, is given by

$$\delta\omega = 157 \cdot 1 \times 2 \cdot 79 \ \delta\theta_1$$
$$= 438 \ \delta\theta_1$$

and when the vernier C_2 is replaced in its position in parallel with C_1 on the oscillator side, the changes of ω will be given by

$$\delta\omega = 438 \times \frac{0 \cdot 638}{6 \cdot 57}\delta\theta_2 = 42 \cdot 6 \ \delta\theta_2$$

The success of these measurements suggests a possible frequency standard. If the natural frequency of the oscillatory circuit were known, it would be easy to find the setting of the oscillator which gives that frequency, and hence to calibrate it. If the oscillator is that of a wave-meter and a number of standards are available, the calibration of the wave-meter would be a far simpler matter than it is at present. The method of the harmonics could be used conveniently to fill in the gaps between the standards.

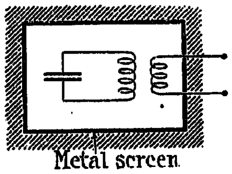

FIG. 17.

The standards could be made up and completely screened and sealed and would consist of a highly efficient oscillatory circuit with a coupling coil, only the terminals of the latter being brought outside the box (Fig. 17). If some device is included for operating a contact in the oscillatory circuit, the whole construction for determining the frequency by drawing the $\delta\omega/\tan\alpha$ curve could be gone through and the frequency obtained very accurately.

But for most purposes a sufficient approximation would be to take the resonant frequency as being that at which the voltmeter reading is midway between the maximum and minimum readings, thus avoiding the necessity for any switch at all. If this is done on Fig. 9 (voltmeter reading) the resonant frequency is obtained at a condenser setting of $63 \cdot 5$, instead of $63 \cdot 2$ from the exact determination. The difference is thus extremely small in this case. In the ammeter method it will be seen from Fig. 11 that the two readings are 106 and 97, a difference of 9, corresponding to a percentage difference in the frequency of

$$\frac{9 \times 42 \cdot 6}{0 \cdot 495 \times 10^6} \times 10^2 = 0 \cdot 078 \text{ per cent.}$$

If, therefore, the frequency of the screened and sealed circuit is determined in the first instance by taking

it as that which gives a reading midway between the maximum and minimum, an accuracy sufficient for all practical purposes should be possible.

Such a standard should be of value to a transmitting station in keeping its wave-length close to that assigned to it. The standard for the station could be made up and sealed by some central authority. At the station it would be connected up in either the voltmeter or ammeter scheme, and a glance at the instrument reading would show any departures. If desired a recording instrument could be fixed so as to have a continuous record of the wave-length transmitted, and incidentally of the times of transmission. Further, the possibility might be considered of making the alterations of current work a relay instead of an indicating instrument, and through the relay controlling in some way the station oscillator so as to keep the transmitted wave-length constant automatically.

Probably the simplest possible arrangement for direct readings of the wave-length would be the ammeter

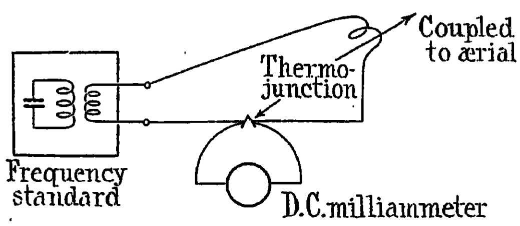

FIG. 18.

one, in which case a thermo-junction could probably be used as indicated in Fig. 18. The only precaution to be taken would be to be sure that the natural frequency of the coupling-coil circuit is far above the frequency in use.

6. MUTUAL INDUCTANCE.

The diagrams obtained make it possible to calculate the mutual inductance between the two coils when their inductances are known. It is clear from the expression $Z/Z_1 = 1 + (\omega^2 M^2/Z_1)(1/Z_2)$ and from what has gone before that at resonance, when $Z_2 = R_2$, the second term gives the diameter of the circle as drawn from the maximum and minimum values of Z/Z_1, and that this is $(\omega^2 M^2/Z_1)(1/R_2)$. Neglecting R_1 in comparison with ωL_1, and calling the diameter of the circle D, we have:—

$$D = \frac{\omega^2 M^2}{\omega L_1} \cdot \frac{1}{R_2} = \frac{\omega M^2}{L_1} \cdot \frac{1}{R_2}$$

and

$$M = \sqrt{\left[\frac{L_1 R_2 D}{\omega}\right]}$$

Applying this expression to the results of Figs. 9 and 11, we have from Fig. 9:—

$$L_1 = 700\ \mu\text{H}$$
$$\omega = 0{\cdot}495 \times 10^6$$
$$R_2 = 9{\cdot}02 \text{ ohms}$$
$$D = 0{\cdot}27$$

and

$$M = \sqrt{\left[\frac{700 \times 9{\cdot}02 \times 0{\cdot}27 \times 10^{-6}}{0{\cdot}495 \times 10^6}\right]} = 58{\cdot}6\ \mu\text{H}$$

From Fig. 11 we have:—

$$L_1 = 700\ \mu\text{H}$$
$$\omega = 0{\cdot}495 \times 10^6$$
$$R_2 = 17{\cdot}23$$
$$D = 0{\cdot}141$$

and

$$M = \sqrt{\left[\frac{700 \times 10^{-6} \times 17{\cdot}23 \times 0{\cdot}141}{0{\cdot}495 \times 10^6}\right]} = 58{\cdot}6\ \mu\text{H}$$

The values given agree very closely, as indeed they should, since the positions of the coils were the same in these two experiments. The measurement of inductance in this way may be useful.

The expression for M can be put into a somewhat different form, viz.:—

$$M = \sqrt{\left[\frac{L_1 R_2 D}{\omega}\right]} = \sqrt{\left[\frac{2L_1 L_2 D}{\omega} \cdot \frac{R_2}{2L_2}\right]}$$

$$\therefore \frac{M}{\sqrt{(L_1 L_2)}} = \sqrt{\left[\frac{2D\Delta}{\omega}\right]}$$

$M/\sqrt{(L_1 L_2)}$ is the coupling coefficient τ between the two coils, so that without any knowledge whatever of the circuit constants the measurements described of the

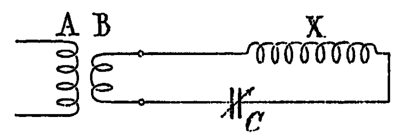

FIG. 19.

decay factor and circle diameter, together with the resonant frequency, give τ.

In the above case (Fig. 9)

$$\tau = \sqrt{\left[\frac{2 \times 0{\cdot}27 \times 1\,118}{0{\cdot}495 \times 10^6}\right]}$$
$$= 0{\cdot}035$$

The agreement obtained suggests that if the coupling remains the same in any series of measurements, and the resistance is measured by drawing out the circle and straight line in one, the resistances in the remaining cases can be determined from a knowledge of the circle diameter only, that is by a measurement of the maximum and minimum values of the ratio Z/Z_1. This leads to a scheme in which only part of the oscillatory circuit B is coupled with the coupling coil A (see Fig. 19). The coils A and B are set up permanently and the resistance/frequency curve of the coil B obtained. The coil X whose resistance is to be measured is then inserted and the circuit is tuned by the condenser C. The knowledge of the mutual inductance between A and B and the resistance of B found from the initial calibration would enable the resistance of X to be obtained from maximum and minimum readings. Some preliminary experiments have been made in this direction, but without very good results. The scheme is perhaps too similar to the substitution method.

7. CONCLUSIONS.

The method of resistance measurement described depends on the knowledge of two quantities only, the

frequency and the value of Z/Z_1. The instruments used to measure Z/Z_1 need not have absolute calibrations as long as they give an accurate measure of the quantity involved.

The essential requirement for accurate measurement is constancy of valve conditions; and, as it is impossible to prevent these changing a little, quick working becomes a necessity. Much time was saved by fitting a critically damped galvanometer in the rectifying-valve voltmeter circuit; this enabled much better results to be obtained.

The advantages of the method are briefly:—

(*a*) The circuit to be tested has no electrical connections made to it and its tuning need not be altered, thus making the method suitable for measuring the resistance of coils at their natural frequency, and in other circumstances where change of tuning is impossible.

(*b*) No absolute measurements need be made except that of condenser change. Other measurements need be only " comparative."

(*c*) The resistance is determined by a number of points lying on a straight line. An estimate of the accuracy of a measurement may be obtained by observing whether or not the points do lie on a straight line.

The value of the mutual coupling does not appreciably affect results, as is shown by the agreement obtained at varying couplings. At tight couplings there may be an error due to losses in the search coil, produced by flux from the circuit to be tested. These losses would appear as extra resistance in the circuit to be tested.*

There can be little doubt that the decay factor of the circuit under test in the circumstances and surroundings under which the test is made is quite accurately obtained. The inaccuracies all occur in converting this decay factor to a resistance, and for many purposes in wireless work this conversion is unnecessary.

The graphical construction appears a little complicated and laborious at first sight, but this is more apparent than real. The measurements and construction with the toroidal coil, made after most of the apparatus had been assembled, were completed within two hours, which included setting up some of the apparatus. The fact that a number of points are obtained which should lie on a straight line is a very helpful guide as to the accuracy of the results, and for this reason it is advisable (at least until one is fairly sure of the constancy of the valve conditions) to include some points outside the steep part of the curve.

Any capacity coupling between the two coils is not sufficient under the circumstances of the tests to influence the results. It was found that to produce a resonance curve with condenser coupling alone, a far greater value for the condenser was necessary than any possible between the coils in their usual positions.

The measurement of the departure of the frequency of a supply from the natural frequency of a given standard circuit can certainly be made with very great accuracy, and this method of frequency determinations may be of value.

A considerable field of investigation is opened up by the results obtained, and it is hoped to continue the work in the Telegraph and Telephone Laboratories of the City and Guilds (Engineering) College, where the whole of the present work was carried out, and where we have had the advantage of discussing our results with Prof. C. L. Fortescue, O.B.E.

* See Appendix 2.

APPENDIX 1.

The Effect of Current Variation.

In the voltmeter method (and similar considerations apply also to the ammeter method) it has been assumed that the current remains constant. This, however, is not strictly the case.

If μ is the amplification constant of the amplifier valve, R_0 its internal resistance and e the voltage applied to the grid by the oscillator, we have for the current through the coil:—

$$i = \frac{\mu e}{R_0 + Z}$$

$$i_1 = \frac{\mu e}{R_0 + Z_1}$$

for the oscillatory circuit closed and open respectively.

In measuring the voltage across the coil, we have accordingly measured iZ and i_1Z_1 respectively, and our ratio is $iZ/(i_1Z_1)$ instead of Z/Z_1 required by the theory. We have for this ratio

$$\frac{iZ}{i_1Z_1} = \frac{\mu e Z}{R_0 + Z} \div \frac{\mu e Z_1}{R_0 + Z_1}$$
$$= \frac{R_0 + Z_1}{R_0 + Z} \times \frac{Z}{Z_1}$$

Substituting the value of $Z = Z_1 + (\omega^2M^2/Z_2)$ the ratio becomes:—

$$\frac{R_0 + Z_1}{R_0 + Z_1 + (\omega^2M^2/Z_2)} \times \frac{Z_1 + (\omega^2M^2/Z_2)}{Z_1}$$
$$= \frac{1}{1 + [1/(R_0 + Z_1)][\omega^2M^2/Z_2]} \times \left(1 + \frac{\omega^2M^2}{Z_1Z_2}\right)$$
$$\doteqdot \left(1 - \frac{1}{R_0 + Z_1} \times \frac{\omega^2M^2}{Z_2}\right)\left(1 + \frac{1}{Z_1} \times \frac{\omega^2M^2}{Z_2}\right)$$
$$\doteqdot 1 + \frac{\omega^2M^2}{Z_2}\left\{\frac{1}{Z_1} - \frac{1}{R_0 + Z_1}\right\}$$
$$= 1 + \frac{\omega^2M^2}{Z_2}\left\{\frac{R_0 + Z_1 - Z_1}{Z_1(R_0 + Z_1)}\right\}$$
$$= 1 + \frac{\omega^2M^2}{Z_2}\left\{\frac{1}{Z_1 + (Z_1^2/R_0)}\right\}$$

neglecting the product of the two small terms.

For the multiplier of ω^2M^2/Z_2 we have therefore a vector constructed as shown in Fig. 20, where OA $= Z_1$, AB$=Z_1^2/R_0$, OB$=Z_1+(Z_1^2/R_0)$ and OD$=1/[Z_1+(Z_1^2/R_0)]$.

The effect of this on the circle will be to depress its diameter through an angle equal to XOD greater than 90°, and this must be taken into consideration in an explanation of the angles of the circle diameter found. Within the limits of the accuracy of the above

calculation there will be no effect on the resistance determination. Also, since OA is very nearly equal to OB, i.e. $Z_1 + Z_1^2/R_0$ very little different from Z_1, the calculation of M in Section 5 will hardly be affected.

In the well-known resistance-variation method of high-frequency resistance * this change of anode current may be very important.

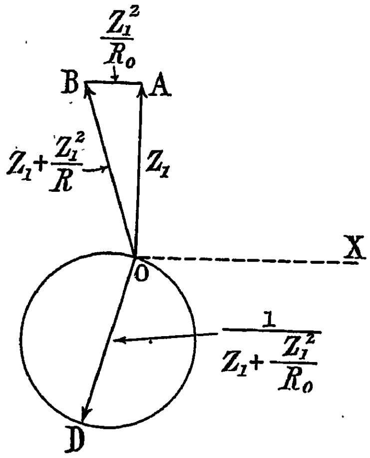

FIG. 20.

In the case shown in Fig. 21 the secondary circuit is tuned and the current I measured by a thermo-junction A. Then a resistance r is added and the current I_1 measured, and $R_2 = \dfrac{r}{(I/I_1) - 1}$ is the formula given for the required resistance.

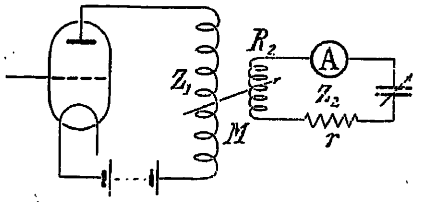

FIG. 21.

Actually, however, if i_a is the anode current, then the E.M.F. into the secondary circuit is $j\omega Mi_a$, and $I = j\omega Mi_a/R_2$.

But
$$i_a = \frac{\mu e_g}{R_0 + Z_1 + (\omega^2M^2/R_2)}$$
so that
$$I = \frac{j\omega M\mu e_g}{R_2(R_0 + Z_1) + \omega^2M^2}$$

Similarly, after r has been added to the secondary,
$$I_1 = \frac{j\omega M\mu e_g}{(R_2 + r)(R_0 + Z_1) + \omega^2M^2}$$
$$\therefore \frac{I}{I_1} = \frac{(R_2 + r)(R_0 + Z_1) + \omega^2M^2}{R_2(R_0 + Z_1) + \omega^2M^2}$$
$$\therefore \left(R_2 + \frac{\omega^2M^2}{R_0 + Z_1}\right)(I - I_1) = I_1 r$$
and
$$R_2 = \frac{r}{(I/I_1) - 1} - \frac{\omega^2M^2}{R_0 + Z_1}$$

* See Bureau of Standards Circular No. 74, p. 180.

If, therefore, no correction is made, the resistance as determined by the usual formula will be too great by an amount $\omega^2M^2/(R_0 + Z_1)$, which may be quite appreciable. It is evident also that adding different resistances r will not solve the difficulty, since the correction $\omega^2M^2/(R_0 + Z_1)$ is independent of r.

APPENDIX 2.

THIRD (UNTUNED) CIRCUIT EFFECTS.

In Fig. 3 we saw how the angle XOD which the circle diameter makes with the horizontal (the whole diagram is turned through a right angle in the constructions from the experimental results, so that O″OX is drawn vertically upwards) is determined in the simple theory by the angle of the impedance Z_1, and how this is modified in the experiments by the small current variation (Appendix 1).

These considerations will explain the angles obtained in most of the experiments, but an exception is found in Fig. 14 where the angle XOD is very large, about 135°. This diagram was obtained at 300 m from the smaller winding of a reaction coil in which the two windings had inductances of 285 μH and 23 μH respectively, and were so tightly coupled that if one had been used as a coupling coil to measure the resistance of the other the voltmeter readings would not have come conveniently within the calibration curve. A separate small coupling coil was therefore wound and slipped over both. Evidently at 300 m the larger coil approached somewhat near to its natural frequency, and thus constituted a third circuit coupled both to the circuit under test and to the coupling coil.

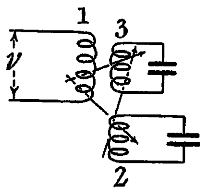

FIG. 22.

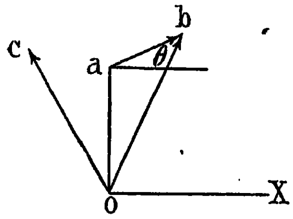

FIG. 23.

The equations for the E.M.F. in the three circuits of Fig. 22 can be written :—
$$\left.\begin{aligned} v &= Z_1i_1 + j\omega M_{13}i_3 + j\omega M_{12}i_2 \\ 0 &= Z_3i_3 + j\omega M_{13}i_1 + j\omega M_{23}i_2 \\ 0 &= Z_2i_2 + j\omega M_{12}i_1 + j\omega M_{23}i_3 \end{aligned}\right\}$$

The manipulation of these is simplified somewhat if, following Wegel,* we write Z_{11} for Z_1, Z_{22} for Z_2, Z_{33} for Z_3 and Z_{13} for $j\omega M_{13}$, Z_{23} for $j\omega M_{23}$ and Z_{12} for $j\omega M_{12}$.

Then the equations become
$$\begin{aligned} v &= Z_{11}i_1 + Z_{13}i_3 + Z_{12}i_2 & (4)\\ 0 &= Z_{33}i_3 + Z_{13}i_1 + Z_{23}i_2 & (5)\\ 0 &= Z_{22}i_2 + Z_{12}i_1 + Z_{23}i_3 & (6) \end{aligned}$$

* R. L. WEGEL: *Journal of the American Institute of Electrical Engineers*, 1924, vol. 40, p. 791.

Eliminating i_3 from (4) and (6) by means of (5) we obtain :—

$$v = \left(Z_{11} - \frac{Z_{13}^2}{Z_{33}}\right)i_1 + \left(Z_{12} - \frac{Z_{23}Z_{13}}{Z_{33}}\right)i_2$$

$$0 = \left(Z_{12} - \frac{Z_{23}Z_{23}}{Z_{33}}\right)i_1 + \left(Z_{22} - \frac{Z_{23}^2}{Z_{33}}\right)i_2$$

When the third circuit is absent ($M_{13} = M_{23} = 0$) we have :—

$$v = Z_{11}i_1 + Z_{12}i_2$$
$$0 = Z_{12}i_1 + Z_{22}i_2$$

as before, giving as our impedance ratio

$$\frac{Z}{Z'} = 1 - \frac{Z_{12}^2}{Z_{11}} \cdot \frac{1}{Z_{22}}$$

In the case with the third circuit present we obtain by symmetry :—

$$\frac{Z}{Z'} = 1 - \frac{[Z_{12} - (Z_{23}Z_{13}/Z_{33})]^2}{Z_{11} - (Z_{13}^2/Z_{33})} \cdot \frac{1}{Z_{22} - (Z_{23}^2/Z_{33})}$$

This equation is now examined vectorially. Z_{11} and Z_{33} are assumed to be sufficiently far from resonance to be taken as constant while the vector $Z_{22} - (Z_{23}^2/Z_{33})$ passes through resonance. It is at once clear that our measurements and construction will give the decay factor and resonant frequency of the vector $Z_{22} - (Z_{23}^2/Z_{33})$ instead of the vector Z_{22}; and that we are now unable to measure these quantities for the vector Z_{22} alone. Also, if the coupling coil is not coupled with the third circuit (i.e. if $Z_{13} = 0$), this is the only effect of the third circuit, since in this case the ratio $[Z_{12} - (Z_{23}Z_{13}/Z_{33})]^2/[Z_{11} - (Z_{13}^2/Z_{33})]$ becomes Z_{12}^2/Z_{11} as before. But if Z_{13} is not zero this ratio will have an angle differing from 90° when the angle of Z_{33} differs from 90°, and its angle will determine the angle of the circle diameter.

If we take
$$\angle Z_{11} = 90°$$
$$\angle Z_{33} = -\theta$$

and draw (see Fig. 23)

$$\text{Oa} = Z_{13}$$

$$\text{ab} = \left| -\frac{Z_{23}Z_{13}}{Z_{33}}\right| \angle\theta$$

then
$$\text{Ob} = \left(Z_{12} - \frac{Z_{23}Z_{13}}{Z_{33}}\right)$$

and
$$\text{Oc} = \left(Z_{12} - \frac{Z_{23}Z_{13}}{Z_{33}}\right)^2$$

drawn so that $\angle$ cOX = 2 $\angle$ bOX.

Oc is the numerator of the ratio. In the denominator we draw (Fig. 24) Od = Z_{11}

$$\text{de} = \left| -\frac{Z_{13}^2}{Z_{33}}\right| \angle\theta$$

and obtain
$$\text{Oe} = \left(Z_{11} - \frac{Z_{13}^2}{Z_{33}}\right)$$

The ratio is therefore given by Of (Fig. 25) where $\angle$ fOX = $\angle$ cOX − $\angle$ eOX and the circle diameter by OD drawn in the opposite direction to Of since it is given by

$$-\frac{[Z_{12} - (Z_{23}Z_{13}/Z_{33})]^2}{Z_{11} - (Z_{13}^2/Z_{33})} \cdot \frac{1}{R_2'}$$

where R_2' is the value of $Z_{22} - (Z_{23}^2/Z_{33})$ at its resonance.

This explains the large angle obtained in Fig. 14. The decay factor of the coil so determined is that of the coil in the presence of the second coil (third circuit),

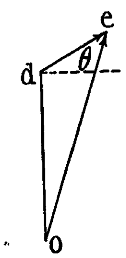

FIG. 24.

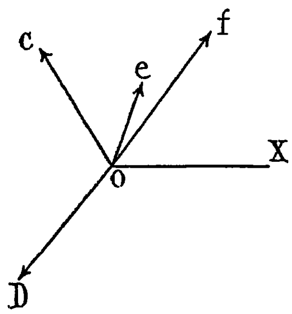

FIG. 25.

and is correctly measured, but the "resistance" has not the simple meaning it has when there is no second coil present. The calculation of the mutual inductance from the circle diameter will also be upset. The angle of the circle diameter thus has a considerable importance in the interpretation of the results; and checks by adding resistance, and measurements of the mutual inductance, cannot be expected to succeed unless the angle conforms with that required by the simple theory, including the current-variation correction given in Appendix 1.

This third-circuit investigation has a more general application to coils. It is usual to take the self-capacity

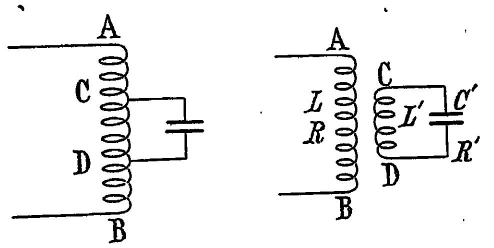

FIG. 26.

of a coil as being in effect a capacity shunting the whole coil AB (Fig. 26). But consisting as it does of a distributed wire-to-wire capacity, perhaps a closer approximation would be given by imagining it shunting only a part, CD, of the coil. Then if the resistance coupling is neglected in comparison with the magnetic coupling, the effect of the self-capacity can be allowed for by a separate circuit having inductance, capacity and resistance, the latter having a value determined not only by the wire resistance of the coil AB but also by the dielectric losses. This constitutes a "third circuit" within

is controlled from the side of a resonance curve, would meet the difficulty cited by Col. Lefroy.

Mr. Cobbold draws attention to the wonderful properties of a quartz crystal resonator. The crystal is a mechanical resonator which can take the place of the oscillatory circuit in the suggested scheme for a wave-length standard over a certain wave-length range. Curves taken * with (a) an ordinary inductance-condenser oscillatory circuit and (b) a quartz crystal under the same conditions are shown in Fig. B. The frequency at resonance is $0\cdot1144 \times 10^6$ cycles/sec. (wave-length 2 164 m), and the frequency scale (horizontal) is 1 255 cycles per sec. per inch. If it is reckoned that the cross-over of the two curves in (a) can be read to within 1/100th inch, the accuracy obtained is $1\cdot255$ cycles in $0\cdot1148 \times 10^6$, or nearly 1 in 10 000, and that is with an ordinary oscillatory circuit with only a moderately good coil. In addition, although the resonance is obviously much sharper with the crystal as shown in (b), the resonant frequency can hardly be read off to a greater accuracy, but this could be obtained by using a smaller vernier condenser. It might therefore be claimed that, far from being out of date, the authors' suggested method for a wave-length standard can be used with the latest form of "oscillatory circuit," the quartz crystal.

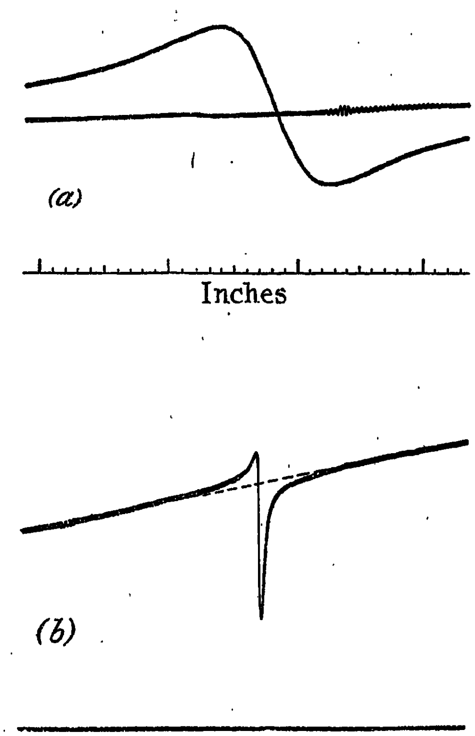

FIG. B.

* By Messrs. E. H. Harding and V. J. Terry, senior students at the City and Guilds (Engineering) College.

But however the crystal is used, it would appear that the precise frequency that is indicated so sharply is not necessarily exactly that of the crystal alone, but (what may be somewhat different) that of the crystal with its associated electrical circuits, and if these circuits have to accompany the crystal its advantage from the point of view of portability will not be so marked. One advantage that the electrical oscillatory circuit would appear to have over the quartz crystal lies in the ease with which it may be adjusted to any desired wave-length.

Mr. Sutton's difficulty when measuring the resistance of a coil at its natural frequency can be overcome quite simply by having a few turns of the "coupling coil" coupled tightly with the coil under test, and the rest not coupled at all. Short-circuiting the few coupled turns will have very nearly the same effect as opening the switch in the oscillatory circuit, and the small inaccuracy introduced can quite easily be corrected. If z is the impedance of the few turns and l their inductance, and Z_1 and L_1 the corresponding values for the rest of the coupling coil, we have with the switch open (see Fig. C),

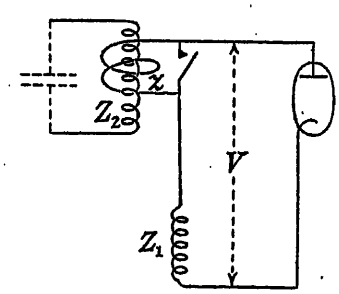

FIG. C.

$$V = \left(Z_1 + z + \frac{\omega^2 M^2}{Z_2}\right) I$$

and with the switch closed

$$V_1 = Z_1 I$$

Hence
$$\frac{V}{V_1} = \frac{Z_1 + z}{Z_1} + \frac{\omega M^2}{Z_1 Z_2}$$

$$\doteqdot 1 + \frac{l}{L_1} + \frac{\omega^2 M^2}{Z_1 Z_2}$$

and the height of the horizontal OA in the construction of Fig. 4 is to be taken as $1 + (l/L_1)$ instead of unity. This procedure could, if desired, be applied to the proposed wave-length standard.

PROCEEDINGS OF THE INSTITUTION.

719TH ORDINARY MEETING, 6 NOVEMBER, 1924.

(Held in the Institution Lecture Theatre.)

Mr. W. B. Woodhouse, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 23rd October, 1924, were taken as read and were confirmed and signed.

A list of donations to the Benevolent Fund (see vol. 62, page 974) was taken as read and the thanks of the meeting were accorded to the donors.

Messrs. J. R. Bedford and J. Hollingworth were appointed scrutineers of the ballot for the election and transfer of members, and, at the end of the meeting, the result of the ballot was declared as follows :—

ELECTIONS.

Members.

Coulston, Percy Barrett.
Lucas, John George.
Price, Joseph Paul.

Associate Members.

Crisp, Miles Henry T.
Day, Francis John.
Hayden, Henry Stock.
Jack, James Mackenzie, B.Sc.(Eng.).
Phillips, Albert Charles.
Thwaites, Richard Alan S., B.Sc.(Eng.).

Graduates.

Amerasinghe, Richard Peter.
Blaquiere, Henry Arnold.
Dunphy, John.
Durrell, William Henry.
England, William Charles.
Hannant, Herbert William M.
Hodge, Thomas.
Laughland, Andrew Percy.
Le Tall, John William, B.A.
Murray, Robert Bruce.
Thompson, Francis Sinclair, B.A.
Waldeck, Thomas Ernest.

Students.

Andrews, Harold Copper.
Ashbee, Ronald Henry.
Ashley, Hugh Hartridge.
Best, Arthur Andrew.
Blakey, Arthur.
Blanden, Frank.
Brickell, Robert Patrick.
Broadbent, Herbert.
Busteed, John William.
Causon, Geoffrey Stephen.
Choudhury, Benoy Chandra.
Clemence, Edward.
Clunie, Matthew.
Coe, David Kenneth A., B.Sc.(Eng.).
Corke, Leslie Cuthbert W.
Davidson, George.
Dean, Jalal.
Dick, Robert.
Dommisse, David Rowell.
Edwards, John Charles.
Farmer, Bernard James.
Fryer, Leslie.
Gall, Alexis Charles.
Gray, Charles Marshall.
Greenway, Horace Eldred.
Greenwood, Ernest Rupert.
Grindrod, Maurice John, B.Sc.
Hammett, William Henry.
Hardwick, John Rosewell.
Harris, Arthur Cyril S.
Harris, James Harold, B.Sc.(Eng.).
Harris Leonard, Frederick.
Henson, William Joseph R.
Illingworth, Thomas.
Josephs, Henry John.

Students—continued.

Kunning, George Alexander.
Lambert, William John.
Lawrie, James Saunders.
Lyall, James Soutar.
Martin, Eric.
Matthews, Charles Edward.
Mellor, Clarence Hedley.
Mullens, Harold Hill.
Nettleton, Claude Stafford.
Newman, Augustus James.
Pawley, Edward Lewis E.
Pedrick, Sydney.
Pengelly, Percy Joseph.
Petrie, William Henry.
Poushkine, George.
Priestley, Frank.
Quenzer, David John.
Rawlinson, Robert (Jun.)
Renshaw, Alfred Percy B.
Sackey, Ebenezer Amos.
Samphier, Leonard Ralph.
Schalit, Salomon.
Scott, Frank Calder.
Smith, Arnold James.
Stewart, John McCulloch.
Stringer, Charles Hubert.
Sykes, John Henry M.
Tatton, Eric.
Thomas, Trevor Henry.
Thorne, Edward Charles.
Tumath, Harold Edward W.
van der Straaten, Philip George.
Waldram, John Malyon, B.Sc.(Eng.).
Williams, Oswald David.
Wilson, Ronald Dennis.
Wright, Hugh Crossley.
Youel, Edward.

TRANSFERS.

Associate Member to Member.

Cameron, Ernest Gordon.
Gaze, Harry Philip.
Lisle, Arthur, M.B.E., B.Sc.(Eng.).
Lower, Richard Anthony.
Mills, Ernest Arthur.

Graduate to Associate Member.

Bleach, Chris Charles.
Havekin, Thomas, B.Sc.
Taylor, Herbert Willott.
Thadhani, Gopaldas Tharumal, B.Sc.

Student to Associate Member.

Amis, Frederick Henry, B.Sc.(Eng.).
Bickell, Stanley Feneley.
Chandler, Wilfred Hardinge.
Dyson, Albert.
Jepson, Cecil.
Pinkney, William Halewood.

Student to Graduate.

Atkins, James Walter.
Beynon, John Henry.
Ferranti, Vincent Gerard S. Z. de.
Fleming, William Kirkland.
Hollis, George Richard.
Kulkarni, Purushottam P., B.A., B.Sc.(Eng.).
Langley, John Edward.
Messent, Keith Santo, B.E.
Moore, Raymond Edward.
Pendleton, Edward.
Purnell, Percival Lawrence.
Russell, Frank Gerald.
Sahgal, Amar Chand, B.Sc.
Spring-Smyth, Harold William.
Thomas, Joseph, M. (Eng.).

The President: I have to announce that the Council have unanimously elected Sir Oliver Lodge an Honorary Member of the Institution. Sir Oliver has been a Member of the Institution since 1889 and his work in electrical engineering has been of a most varied kind. His early work was in connection with the flow of electricity through metals, electrolytes and dielectrics, on the resistance of alloys, and on the phenomena of self-induction and mutual induction. When he was Professor of Physics at Liverpool he conducted a series of experiments on secondary batteries, and later devoted his attention to electrolysis, electrical discharges and the electrical precipitation of particles in the air, a subject which is becoming more and more important. Although we know the very great and valuable work he has done in so many fields, his name is most intimately connected with the subject of wireless telegraphy. The importance of his 1897 invention for adding an inductance in an oscillating radiating system, for the purpose of tuning and increasing the persistence of oscillations, cannot be overestimated. It was an extremely valuable addition to the art in its infancy and has been adopted in every form of succesful radiotelegraph transmitter, whether of the spark, arc or high-frequency alternator type. In 1914 he delivered before the Institution the Fifth Kelvin Lecture on "The Electrification of the Atmosphere, Natural and Artificial." Sir Oliver has received many honours: he is a Fellow of the Royal Society, he has been President of the British Association, and he has been a distinguished teacher both at Liverpool and at Birmingham. I am sure that members will join with the Council in desiring to offer him an additional honour by electing him an Honorary Member of the Institution.

The members present unanimously signified their approval.

A paper by Messrs. J. D. Cockcroft, R. T. Coe, J. A. Tyacke, Students, and Prof. Miles Walker, Member, entitled "An Electric Harmonic Analyser" (see page 69), was read and discussed.

On the motion of the President a hearty vote of thanks was accorded to the authors, and the meeting terminated at 7.45 p.m.

720TH ORDINARY MEETING, 20 NOVEMBER, 1924.

(Held in the Institution Lecture Theatre.)

Mr. W. B. Woodhouse, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 6th November, 1924, were taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

A paper by Mr. G. Rogers, Associate Member, entitled "Automatic and Semi-Automatic Mercury-Vapour Rectifier Substations" (see page 157), was read and discussed.

On the motion of the President a vote of thanks to the author was carried with acclamation, and the meeting terminated at 7.50 p.m.

41ST MEETING OF THE WIRELESS SECTION, 3 DECEMBER, 1924.

(Held in the Institution Lecture Theatre.)

Mr. E. H. Shaughnessy, O.B.E., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 5th November, 1924, were taken as read and were confirmed and signed.

A paper by Mr. G. Shearing, B.Sc., Member, entitled "Wireless Telegraph Valve Transmitters Employing Rectified Alternating Current" (see page 309), was read and discussed.

On the motion of the Chairman a vote of thanks to the author was carried with acclamation, and the meeting terminated at 7.50 p.m.

721ST ORDINARY MEETING, 4 DECEMBER, 1924.

(Held in the Institution Lecture Theatre.)

Mr. W. B. Woodhouse, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 20th November, 1924, were taken as read and were confirmed and signed.

A list of donations to the Benevolent Fund (see page 68) was taken as read and the thanks of the meeting were accorded to the donors.

Prof. J. G. Gray, D.Sc., assisted by Mr. J. Gray, then delivered a lecture on "Gyroscopic Pendulums," which was accompanied by a demonstration.

On the motion of the President a vote of thanks to the lecturer was carried with acclamation, and the meeting terminated at 7.30 p.m.

722ND ORDINARY MEETING, 18 DECEMBER, 1924.

(Held in the Institution Lecture Theatre.)

Mr. A. Page, Vice-President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 4th December, 1924, were taken as read and were confirmed and signed.

The following list of donors to the Library was taken as read, and the thanks of the meeting were accorded to the donors :—

Library : Meteorological Office, Air Ministry; American Institute of Electrical Engineers; American Railway Association; Astronomer Royal; Messrs. E. Benn, Ltd.; A. Blanchard; Board of Education; O. Bonazzi; British Empire Exhibition Committee; British Engine Boiler and Electrical Insurance Co., Ltd.; British Engineering Standards Association; British Non-Ferrous Metal Research Association; Messrs. Butterworth and Co.; Dominion Water Power Branch and the Government Trade Commissioner, Canada; Messrs. Chapman and Hall, Ltd.; R. A. Chattock; Chief Inspector of Factories; Comptroller General, Department of Overseas Trade; Messrs. Constable and Co., Ltd.; H. Cotton, M.B.E.; Department of Scientific and Industrial Research; H. M. Dowsett; Dr. C. V. Drysdale, O.B.E.; Electrical Contractors' Association; "Electrical Review"; Electricity Commissioners; C. F. Elwell; Engineering Institute of Canada; E. A. H. French; J. Frith; E. Garcke; Sir Robert Hadfield, Bart., F.R.S.; H. H. Harrison; G. M. Harvey; S. B. Hickin; High Commissioner for Canada; High Commissioner for the Union of South Africa; H. M. Hobart; Hydro-Electric Power Commission of Ontario; Imperial Mineral Research Bureau; Incorporated Municipal Electrical Association; Institution of Engineers, Australia; Institution of Railway Signal Engineers; John Crear Library; A. C. Jolley; Prof. A. E. Kennelly; Kristiania Geofysiske Kommission; Messrs. Marconi's Wireless Telegraph Co., Ltd.; G. Marie; R. E. Neale; Det Norske Meteorologiske Institut; M. Otagawa; Advisory Research Council, Ottawa; E. T. Painton; W. H. Patchell; Messrs. E. F. Phillips's Electrical Works, Ltd.; Messrs. Sir Isaac Pitman and Sons, Ltd.; W. L. Randell; Messrs. S. Rentell and Co., Ltd.; S. R. Roget; Royal Albert Observatory, Mauritius; Dr. A. Russell, F.R.S.; H. M. Sayers; Schweizerischer Elektrotechnischer Verein; J. Scott-Taggart; Signals Experimental Establishment, Woolwich; Messrs. Smith, Kempe and Smith; Société des Ingenieurs Civils de France; Messrs. E. and F. N. Spon, Ltd.; Surveyor-General of India; W. T. Taylor; H. F. Trewman G. E. Tripp, LL.D.; Under-Secretary for Mines; S. Velander; E. B. Wedmore; W. Wilson; The Wireless Press, Ltd.; and Lady Yarrow.

A paper by Mr. Donald Murray, M.A., Member, entitled "Speeding up the Telegraphs: A Forecast of the New Telegraphy" (see page 245), was read and discussed, and a demonstration of printing telegraphs was given.

On the motion of the Chairman a vote of thanks to the author was carried with acclamation, and the meeting terminated at 7.45 p.m.

42ND MEETING OF THE WIRELESS SECTION, 7 JANUARY, 1925.

(Held in the Institution Lecture Theatre.)

Mr. E. H. Shaughnessy, O.B.E., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 3rd December, 1924, were taken as read and were confirmed and signed.

A paper by Professor E. Mallett, M.Sc., Member, and Mr. A. D. Blumlein, Student, entitled "A New Method of High-Frequency Resistance Measurement" (see page 397), was read and discussed.

On the motion of the Chairman a hearty vote of thanks was accorded to the authors for their paper, and the meeting terminated at 7.40 p.m.

723RD ORDINARY MEETING, 8 JANUARY, 1925.

(Held in the Institution Lecture Theatre.)

Mr. W. B. Woodhouse, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 18th December, 1924, were taken as read and were confirmed and signed.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

A list of donations to the Benevolent Fund (see page 155) was taken as read and the thanks of the meeting were accorded to the donors.

A paper by Mr. H. W. Taylor, Associate Member, entitled "Three-Wire Direct-Current Distribution Networks: Some Comparisons in Cost and Operation" (see page 337), was read and discussed.

On the motion of the President a hearty vote of thanks to the author was carried with acclamation, and the meeting terminated at 7.50 p.m.

724TH ORDINARY MEETING, 22 JANUARY, 1925.

(Held in the Institution Lecture Theatre.)

Mr. W. B. Woodhouse, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 8th January, 1925, were taken as read and were confirmed and signed.

Messrs. A. E. Kennard and A. W. Marshall were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the result of the ballot was declared as follows :—

ELECTIONS.

Members.

Appleyard, Rollo, O.B.E., J.P., Commander, R.N.V.R.
Boulton, Percival Raymond.
Murdoch, William Henry F., B.Sc.

Associate Members.

Allan, David Taylor.
Carter, Joseph Walter.
Dalley, Christopher.
Erlebach, Wilfrid Arthur, B.Sc.(Eng.).
Everett, Reginald Marsh.
Harris, Thomas Emlyn.
Jackson, Henry, B.Sc. (Eng.).
Lakeman, Henry George.
Linzell, Harry.
Orbell, Robert Hugh.
Page, Albert, B.Sc.
Partridge, Charles Frederick, B.Sc.(Eng.).
Payne, Douglas Harold.
Peronne, Philippe Ernest.
Proctor, Roland Faraday, B.Sc.(Eng.).
Richards, Reginald, B.Sc. (Eng.).
Rowles, Henry Percival.
Smith, Donald George, B.Sc.(Eng.).
Stevenson, George Eugene.
Toplis, William Sharman.
Varney, Theodore, B.Sc.
Welch, Frederick Maurice.
Wiseman, Robert Joseph, D.Sc.

Graduates.

Allen, James.
Bailey, Roland Frederic, B.Sc.(Eng.).
Balasubramanian, M.S., B.A., B.E.
Ball, Alfred.
Beney, Harry.
Bhargava, Goverdhan Prasad.
Bishop, John Leo.
Bull, Walter John H., B.Sc.
Campbell, Percy Oliver.
Cass, Vernon Sydney.
Chase-Currier, Victor Charles.
Clarke, Albert Edward.
Curd, David Alfred G.
Dickson, William Laybourne E., B.Sc.(Eng.).
Gangoly, Umadhava, M.Sc.
Giles, Ralph Bostock.
Gogan, James.
Green, George Ernest.
Grimmitt, Howard Walker.
Hahn, Otto Henry, B.Sc. (Eng.).
Harrison, Harold Edward.
Johnston, Reginald James.
Jones, Reginald Hugh, M.Sc.(Eng.).
Joshi, Gopal Anant, B.A., B.E.
Keast, Norman Radden.
Kirtikar, Shrikrishna.
McGuigan, William.
Masters, Thomas Bertram.
Musson, Stanley Ford.
Nadhan, Vaiankalatur Ramaswami H.
Narbeth, Charles Anstey.
Pardoe, Leonard Gardiner, B.E.
Provand, Ninian.
Savage, Joseph.
Sen, Mahendra Nath.

Graduates—continued.

Somayajulei, Bulusu Rama
Srinivasa Moorthy Rao, Srinivasarao.
Subramanian, Mrityunjaya.
Thompson, Thomas Barnes.
Upasena, Esapala.
Walker, Herbert.
Ward, George.
Waring, Alfred James.
White, Ernest Henderson.
Whitehead, John Herbert, B.Sc.Tech.
Wijisinghe, Don Martin.
Wyatt, Thomas Harold.

Students.

Adams, Andrew Walter.
Albert, James William.
Allen, Bernard Geeson.
Allen, Carrol.
Andrew, Alfred Joseph.
Atherton, John Henry.
Atkins, Hubert Cyril.
Atkinson, Cyril Nicholas.
Atkinson, William Scott.
Baker, Sidney Henry.
Barlow, Stuart Lansdale M.
Beach, Arthur Ernest.
Bearn, James, B.Sc.(Eng.).
Beattie, William Blackwood.
Beaufoy, Samuel.
Belcher, Cecil Albert.
Bennett, James.
Bentley, Lawrence Cranmer.
Berkeley, Bernard Bruce F.
Berryman, Benjamin Henry J.
Bitter, Augustus Edward.
Blayney, Thomas Garland.
Blenheim, Donald Eugene.
Bloemsma, Jan.
Bowker, Henry Charles.
Brewster, Leonard William
Briggs, Charles Stanley.
Brockwell, Reginald William.
Brown, Henry Austen.
Brown, Walter Robinson.
Burgess, Charles Edward.
Bush, Horace.
Butler, Cyril Dean.
Caldwell, George Alexander.
Campbell, Duncan.
Campbell, Ian Drummond.
Cash, Peter Watson.
Catten, Thomas.
Chalmers, William Burns B., B.Sc.
Chapman, Reginald Henry.
Chatterji, Phanindra Mohan, B.Sc.
Chaudhuri, Joy Deb.
Chew, Francis Noel.
Child, Ivon Henry.
Chrisp, Oswald Alexander.
Clark, Ronald Isaac H.
Clayton, Harry.
Clement, John.
Clifford, Clifford Hugh.
Clissold, Frank Willoughby.
Coates, Raymond Henry.
Coleman, William Henry J.
Collis, William Blow G.
Connelly, Denis.
Cook, William Arthur.
Cooper, Walter Fletcher.
Coupland, Leonard Frederick.
Craddock, Reginald Robert.
Croucher, James Alfred.
Cuerden, Thomas Gordon.
Cutmore, Reginald Richard.
Dain, Frederick Charles.
Daniel, Leslie Henry.
Darmanin, Hector.
David, Neville.
Davies, William Arthur.
Davis, Robert Courtney.
Dean, Edward Timothy.
Debney, Charles Edward.
Dick, George.
Dickie, William John.
Dickinson, Herbert George B.
Ditmas, John Mesham R., B.A.
Dixon, Stanley Henry.
Dobbie, Robert George M., B.Sc.
Drabble, Arthur Frederick.
Drake, William Edward J.
Duckworth, Laurence Sidney.
Dunsford, Edwin Henry.
Durbin, James.
Dykes, John.

Students—continued.

Elliott, Ernest.
Escott, Alexander John.
Evans, Rhys.
Evans, Ronald Coyle.
Evans, William Freeman.
Ford, Wallace.
Foskett, Ronald Stanley.
Fountain, Leslie Arthur.
Fox, Stanley Charles E.
Franklin, Arthur James.
French, David Charles.
Fuller, Arthur Leslie.
Gabriel, Samuel Lewis D.
Gangoli, Nehar.
George, C. Francis.
Gerard, Arthur Geoffrey L.
Gibson, William.
Gilbert, John Edward.
Gill, Francis Cawthra.
Glew, Frederick Stanley.
Goodman, Arthur.
Goodwin, Douglas Ahearn.
Gorkiewicz, Richard.
Gower, Sydney Clayton.
Grant, Patrick Seafield.
Green, Robert James P.
Greenwood, Albert Edward.
Greenwood, John Herbert.
Gurney, Norman Richard D.
Hall, Donald Leslie.
Hall, Philip Stedman.
Hamp, George Alexander.
Hardisty, Rupert Woodville.
Harper, Cecil Thomas A.
Harrabin, Frank.
Harrison, Neville Isaac B.
Harthan, Edmund Pring.
Hawkesley, Edgar.
Hawley, Philip Alan.
Hayat, Mohammad.
Hayes, James Henry.
Hedgecock, Edward.
Hill, John Bartholomew.
Hind, Harold Stanley.
Hinds, George Alfred R.
Hirshman, Cyril.
Hirst, Alexander William C.
Hodkinson, John Clifford.
Hogg, Thomas Mylne.
Hoggan, Leslie Edward A.
Holland, Albert Eric.
Holmwood, Kenneth Arthur.
Hughes, Cecil.
Hughes, John Gilbertson.
Hutchen, Alan Frank.
Hutter, Henry Edmond.
Ignatieff, Nicholas.
Jackson, Edward Gerald H.
Jackson, Willie.
James, Douglas John.
Jewell, Edward Horace T., B.Sc.
Jones, Elwyn, B.Sc.
Jones, Harold Edward.
Kamen, Maurice.
Karkaria, Adi Jehangir.
Kenyon, Alec Hindle.
Kerr, William John.
Khan, Mohamed Afzal Ali, B.Sc.
King, Cyril Matthew.
King, Frederick Joseph.
Kitching, Philip Henry.
Kniveton, Allan Aspinal.
Krishna Rao, Sivanapur, B.Sc.
Lackie, David Lamond, B.Sc.
Land, James Edward.
Ledsom, Alexander.
Leftley, Joseph Richard.
Leigh, Harold.
Leslie, Bernard Heriot P.
Lewis, Frederick William M.
Lithgow, Douglas Lockhart B.
Low, William Kemp.
McCartney, Hugh.
McCormac, Arthur.
McInman, Meredith Charles.
Mackersey, Colin Alleyne.
Macnee, Douglas Hamilton.
Maggs, Percy James.
Mansford, Hugh Lyon.
Marlow, Dennis Herbert.
Martin, John Anthony F.
Masterman, Christopher Edward.
Mathews, Ernest Samuel.
May, George Egerton.
Mayer, Cornelius Geerts.
Maynard, Stanley Payne.
Meswani, Vasanji Mulchand.
Middleton, Robert Allan.
Mitchell, Henry Ledger.
Moody, George John.
Moores, Frederick Ronald.
Morrill, Albert Edward.
Moussa, Mohamed.
Muir, Donald Somerville.
Murray, Cyril.
Neal, Cyril Arthur.
Nixon, William Geoffrey J.
O'Connor, Charles Patrick.
Offord, George Robert.
Osment, Cyril George.
Pack, Stanley Walter C.
Page, Robert Burton.
Panton, Reginald.
Parke, Dudley Wainwright.
Parker, William Alfred.
Parsons, Reginald Alfred E.
Patton, William Archibald H.
Peall, George Strickland H.
Peaston, Clifford John.
Pemberton, William.
Peters, Alan Neil.
Pettitt, Leslie William.
Phillips, Ivor Heath.
Phillips, Leonard Hamlyn J.
Pierce, Robert Frank R.
Piercy, Raymond Hugh S.
Pilcher, Richard Hessey.
Possnett, Arthur Frederick J.
Potter, William Henry.
Pritchard, Arthur Lennox.
Pugh, David William.
Raisin, Aubrey Howard.
Ralph, Tom.
Ramasawmi, Alappakkam Varadachary.
Rawll, Stanley Charles.
Rayner, William Eric.
Redclift, Ronald David.
Reddi, Chithathurai Govindurajulu.
Reddy, Pingle Janardan.
Reed, Morris.
Reynolds, Basil William.
Rhodes, John Kenneth.
Rhodes, Joseph William.
Rickett, Owen Charles.
Rigg, Robert.
Roberts, Edwin Reece.
Robertson, Bertram Howard, B.Sc.
Robertson, Eric Stanley.
Rocha, Carlos de Seixas.
Roger, Alfred John R.
Rogers, Thomas Howard.
Rundle, John Leslie, B.Sc. (Eng.).
Ryan, Patrick Leo.
Sage, Edgar Thomas.
Schou, Gaston Recardo.
Sen, Rajani Kumar, B.Sc.
Seshagiri Rao T., B.Sc.
Shankariah, Nagalapur Seshasastri, B.Sc.
Sharma, Dev Datt, B.Sc.
Shaw, Stanley Ker.
Shepherd, William Raymond.
Shirley, George Edward.
Shrivastava, Harinarayan Lal.
Sibal, Bisheshwar Nath, M.Sc.
Simmonds, Henry.
Simon, Eric William.
Skoulding, John Horace.
Slade, Alexander Henry.
Smith, Dennis Harry.
Smith, Douglas MacLeod.
Somervell, Ronald Arthur B.A.
Somerville, Arthur Walter M.
Souter, William Thomas F.
Soutter, Cedric Guy.
Stephens, Richard.
Stephens, Rupert Douglas.
Stephens, William Charles.
Stevens, Sydney Arthur.
Stevens, Thomas Frederick.
Stock, John Miles.
Stockley, Arthur Chamberlain.
Storrar, Jack Hector.
Straw, John G.
Strevens, Ernest Leslie.
Stribley, Leslie Wills.
Swift, William Harold.
Sydenham, Reginald James.
Tankosai, Wake.
Thomas, George Herbert.
Thorp, Gilbert Hanley.
Tombleson, Harold.
Towers, Frederick William G.
Towes, George Fredrich.
Tucker, Valentine.
Turnbull, Ian Love.
Tyrrell, Gilbert Charles.
Tyson, William Reginald.
Vedanthiengar, Komandur.
Vizard, Herbert James.
Waddle, Robert Alfred, B.Sc.
Waite, William Eric.
Walker, Gordon, Mabor.
Warlow, Arthur James P.
Waring, John Noel.
Warrington, Richard Mervyn.
Webb, Allen Ashard.
Weisman, Barnett.
Weller, Herbert Lewis.
Westwood, Edgar Fred.
Wethered, Harold Edmund.
White, Adam Watson.

Students—continued.

Whittle, Norman Edward.
Williams, Benjamin Jones.
Williams, Edgar Ledger.
Wilson, Eric.
Wiltshire, Herbert Charles, B.Sc.
Woods, Harold, B.Eng.
Woods, Reginald Arthur.
Wray, John Alan.
Wright, Colin.
Wright, Herbert (Jun.)
Wright, Walter James.
Yeung, Shiu Hong.
Yews, Douglas Clement.
Young, Harry Robert.
Young, Martin Henry.

Associate.

Gardner, George Anthony.

TRANSFERS.

Associate Member to Member.

Beetlestone, Mark Arthur.
Buckley, Percival, Capt., R.E.(T.)
Bush, Paul Francis W., Capt., R.A.F.
Calman, Cecil George.
Chatterjee, Bhim Chandra, B.A., B.Sc., B.L.
Del Mar, William Arthur.
Fippard, Arthur John.
Henderson, Matthew Cochrane.
Kemp, Charles Richard.
Monaghan, Thomas Joseph, B.Sc.(Eng.).
Pannell, Ernest Vincent.
Perrin, Cecil Marsden.
Robertson, Robert Knight.
Ryan, Mervyn Frederick.
Sorby, Vincent Dare.
Stanton, Albert Lennox.
Stephens, John Newton.
Wilson, James Laing.

Associate to Member.

Unbehaun, Albert Carl.

Graduate to Associate Member.

Browne, Arthur William.
Batham, Guy Symonds M., B.Sc.
Dalton, George Allan.
de Oliveira, Antonio Carlos.
Dickinson, James, M.A., M.Eng.
Glasse, Alfred Onslow.
Guthrie, Alec, B.Sc.(Eng.).
Jones, David William G.
Mackay, William Morton, B.Sc.
McLaughlan, Bernard Alphonsus.
Miller, David McRoberts.
Molle, George William.
Morgan, Hedley Edmund.
Murray, Robert Bruce.
Onslow, David Victor.
Payne, Norman Burkett.
Robson, Charles William, B.Sc.
Rogerson, Robert.
Sarsfield, Leslie Gerald H., B.Sc.(Eng.).
Sclar, Isaac.
Stevens, George Carson.
Swale, William Eric.
Williams, Bertram Evan.

Student to Associate Member.

Allam, Eric Bertram.
Baxendale, Frank, B.Sc. (Eng.).
Butterworth, Hubert.
Chapple, Harry John B., B.Sc.(Eng.).
Cousins, Cyril George, B.Sc.(Eng.).
Grose, Stewart Jewell, B.Sc.(Eng.).
Harvey, Arthur Frederic S.
Heatly, William Gladstone, B.Sc.(Eng.).
Jolin, Charles Henry, B.Sc.(Eng.).
Keet, Alan Livingstone, B.Eng.
Matthews, William Thomas.
Needham, Joseph Frank W., B.Sc.
Nixon, John Humphrey R.
Piquet, John.

Student to Associate Member—continued.

Powell, Edward Blennerhassett S.
Russell, John, B.Sc. (Eng.).
Strickland, Albert Macdougall.
Stuart, Walter Stanley, B.Eng.
Trelease, John Stanley, B.Sc.Tech.
Turton, Leonard, B.Eng.
Unwin, Dudley James.
Webb, Clifford Ernest, B.Sc.(Eng.).
Wilman, Charles Wilfrid.

Student to Graduate.

Alder, Charles Daniel, B.Sc.
Atkins, William Thomas J., B.Sc.(Eng.).
Avison, Robert Geoffrey.
Baker, Charles Hale.
Barson, Albert Clifford, B.Sc.(Eng.).
Bennett, Horace William J.
Bent, Fred.
Bishop, Edgar Richard.
Blackler, Clarence William.
Bunt, Noel Barnden.
Charles, Norman Henry, B.Sc.(Eng.).
Clegg, Percy, B.Sc.Tech.
Cox, Robert Stuart W.
Cruttwell, Colin Edward, B.Sc.(Eng.).
Davies, William Richard.
Easter, Charles Edward.
Ezard, Gerald.
Ferguson, Robert Hugh, B.Sc.
Filbey, Charles Albert.
Gardiner, Herbert William B., B.Sc.(Eng.).
Gosling, Arthur John B.
Hall, Harry, B.Sc.Tech.
Hullah, Roland Gilbert.
Kelly, Maurice James.
Lamerton, Henry, B.Sc. (Eng.).
Leyland, Arthur James, B.Sc.Tech.
Maiden, Reginald Stuart.
Nadkarni, Ananh Pandurang.
Norris, Harry.
Norton, Leopold Gerard.
Novaes, Paulo de Oliveiria.
O'Brien, Brian, M.Eng.
O'Meara, Esmonde.
Paine, George Richard.
Pegg, Reginald Noel.
Pick, Thomas Sisson, B.Sc.(Eng.).
Pillans, James Pritchard S.
Rayner, Frederick John.
Ridley, Allison.
Russell, Robert.
Scaling, Thomas Nawton.
Scrafton, Christopher Dixon.
Springsguth, Charles Edward.
Stearn, George Fletcher, M.A.
Sutcliffe, Tom Halliwell, B.Sc.Tech.
Thomas, Cyril Marsingall.
Thomas, Leonard.
Thomas, William Neam, B.Eng.
Vicario, Victor Charles.
Waterhouse, Clifford Thwaite.
Westell, Edgar Philip L.
Wills, Felix Percival, B.Sc.(Eng.).
Winfield, Frederick C., M.Eng.
Wynne, Richard.

The President: The next business is unusual but very welcome. We have with us this evening Mr. J. Ferguson Bell, President of the Institution of Gas Engineers, with a deputation from his Council, and I propose to ask him to explain the object of their visit.

Mr. J. Ferguson Bell: I should like in the first place to thank the members for their very cordial welcome. I have attended for the purpose of asking the Institution to accept an engraved plate and a framed presidential certificate, which will be presented to Dr. Alexander Russell, who was President last

session. This certificate is signed by the present President, Mr. Woodhouse. At the Annual Meeting of the Institution of Gas Engineers last year, a presidential certificate designed by Mr. F. D. Marshall was presented by me to our retiring President, Mr. Samuel Tagg, in commemoration of his year of office. The certificate was exhibited in this building, where our meetings were held, and was much admired. Our Council desired to make some tangible acknowledgment of the kindness that we have received from the Institution, not only last year but in former years, in giving us the free use of these fine premises for our meetings, and we therefore thought that we should like to express in some form our appreciation by presenting to the Institution a souvenir, which has taken the form of a presidential certificate. The acceptance of this engraved certificate indicates the good feeling that happily exists between the members of both Institutions, and I venture to say that we hope this happy feeling of friendliness will long continue. I should like now to strike a personal note and mention that 30 years ago I was associated with the late Dr. John Hopkinson. Mr. J. S. Highfield was also associated with me at the Stafford Corporation Electricity Works. In those days electricity was in its infancy; it was considered a luxury. So far back, however, as over 30 years ago—I believe that the date was 1890—I advised the Corporation to erect an electricity works. I told them that electricity had a great future, and that it eventually would become one of our important public utility services. That forecast has been fully justified; and the great advance made by electricity, due to the high technical skill, the enterprise, and the efficiency of the various members of the Institution, is indicated by the enormous use that is now made of electricity for very many purposes. The advance of light and power is indicated on all hands and in many directions. The importance of electro-chemistry may be gauged by the fact that many products now on the market are made by electrical processes which in some instances are doing away with the older processes. Electro-metallurgy applied to the products of chemical reactions and molecular changes at furnace temperatures are well known. Electricity is also used in most of our great infirmaries and hospitals for the alleviation of suffering and pain. We also know the enormous advance which has been made in the development of the telephone, and then we have the almost incredible wonders of wireless. All these indicate the immense and the alluring pursuits in the further application of electricity. It may be that in years to come we shall get a great deal of energy from sources other than coal. I think that that will be to the advantage of the community, because our supplies of coal are not altogether inexhaustible. Coal is dear, and thus if electricity can be generated from other sources and coal saved for those processes for which it is essential, electrical engineers will be conferring a further benefit on the community. In conclusion, I should like to congratulate the electrical industry upon the well-known scientific men—I might say brilliant scientific men—who are engaged within its ranks and who are supported by well-trained, enthusiastic younger men. Also, it is well supported by its technical Press. All these have tended towards the extension of electricity. On behalf of the Institution of Gas Engineers, which the deputation represents, I wish the Institution of Electrical Engineers continued prosperity; and in this connection we members of the Institution of Gas Engineers believe that there is ample scope for both industries to prosper. There must at times be inevitable competition between the different forms of energy, but competition tends to progress, and competition, so long as it is reasonable, is to the benefit of both our industries. I do not think, speaking for the gas industry, that we should have made so much progress during the last quarter of a century if we had not been pushed forward by electrical engineers. It is with the greatest pleasure that I ask the President to accept this presidential certificate, along with the engraved plate from which it is a first impression and from which I hope that he will later receive a certificate for himself.

Mr. Bell then formally presented to the President the engraved plate and the presidential certificate, the latter being in a gilt frame and containing the following words:—

"Institution of Electrical Engineers, Founded 1871, Incorporated by Royal Charter 1921. This is to record that Dr. Alexander Russell, LL.D., F.R.S., held the office of President for the year 1923–24. Witness our hands and seal this 8th day of January, 1925. (Signed) W. B. Woodhouse, President; F. Gill, Member of Council; P. F. Rowell, Secretary."

The President: I have very great pleasure in accepting, on behalf of the Council of the Institution of Electrical Engineers, this charming certificate, carrying out the very artistic and appropriate design which Mr. F. D. Marshall has been kind enough to prepare. In granting to the Institution of Gas Engineers the use at times of this lecture theatre we did not expect any such tangible return as this. We ourselves in the past have been the guests of other scientific Institutions, and we are very happy now to be in a position to show hospitality to other engineering societies. I am sure I am only voicing the views of all the members in saying that we appreciate very deeply indeed this graceful act on the part of the members of a sister engineering Institution. The members of the Institution of Gas Engineers, like many of our own members, are concerned with the proper utilization of coal, and probably the differences of opinion which exist as to what is quite the best way to do it are apt to overshadow the very numerous and very important interests which we have in common. We are both attempting to solve the same problem. We have very largely worked on independent lines, but we who are engaged in the supply of electricity to the public are very much indebted to the gas engineers for having first of all made the public aware that they could purchase a means of light, of heat, and of power from a public source, and that they could turn on the tap and get just as much or just as little as they wanted. When we came on the scene with another means of light, heat and power we had a public which was to some extent educated. I look forward in the future to

a closer approach between all those who are engaged in the utilization of coal. Gas engineers, those who are engaged in producing coke for metallurgical purposes, those who are engaged in mining coal, and ourselves, are all closely and very deeply concerned in finding the best possible way to use that coal, and the best possible way to bring to the public the light, the heat and the power that they require. I think the present occasion is a very happy augury of future association in discussing such matters. I believe that a discussion of our common problems, as well as a discussion of our differences, will be all to the good. I am sure we are all at one in the object in view, which is to make the best possible utilization of our national resources of coal in every possible way. I am very glad to accept, on behalf of the Institution, this kind gift, and I now have to ask Dr. Alexander Russell, as the immediate Past-President, to accept this very handsome certificate as a record of his year of Presidency.

The President then presented the certificate to Dr. Alexander Russell, and the deputation withdrew.

The President: I have pleasure in announcing that at their meeting held this afternoon the Council decided to award the Faraday Medal to Sir Joseph John Thomson in recognition of the distinguished work which he has done for electrical science. Sir Joseph's work is so well known that there is no need for me to refer to it in detail, but I may remind the members that he is an Honorary Member of our Institution, and we are proud to offer him this additional recognition of our appreciation.

A paper by Mr. H. W. Clothier, entitled "The Design of Electrical Plant, Control Gear and Connections for Protection against Shock, Fire and Faults" (see page 425), was then read and discussed. On the motion of the President a hearty vote of thanks was accorded to the author for his paper, and the meeting terminated at 8 p.m.

INSTITUTION NOTES.

Associate Membership Examination Results, February, 1925.

ROYAL CORPS OF SIGNALS.

Passed in "The Theory of Electrical Military Signalling."

Charlesworth, Lieutenant J. F., Middlesex Regiment.
Gray, Lieutenant F. P. L., R. Inniskilling Fusiliers.
Knight, Lieutenant C. W., Royal Artillery.
Newington, Captain M. T. L., 18th K.E.O. Cavalry.
Paterson, Second-Lieutenant D. R., Royal Signals.
Peachell, Lieutenant W. A., Q.O. Royal West Kent Regiment.
Raikes, Lieutenant R. F., 2/15th Punjab Regiment.
Roberts, Captain V. P., 16th Light Cavalry.
Rowley, Captain B. G., 14th Punjab Regiment.
Salter, Captain E., 1/3rd Q.A.O. Gurkha Rifles.
White, Lieutenant C. M. F., Royal Artillery.
Wilson, Lieutenant F. K., Gloster Regiment.

National Certificates and Diplomas in Electrical Engineering.

The following Institute has been approved under the scheme drawn up by the Board of Education and the Institution :—

Approved for Higher Grade Certificates (Advanced Part-time Course).

Borough Polytechnic Institute.

Third International Conference on Large Electric Supply Systems.

The Council of the Institution have nominated the following to be the British official delegates at the above Conference (see *Journal I.E.E.*, vol. 62, page 974) to be held in Paris from the 16th to the 25th June :—

Mr. W. B. Woodhouse (first British delegate),
Mr. A. R. Everest,
Mr. P. V. Hunter, C.B.E.,
Mr. A. Page,
Mr. E. B. Wedmore.

Additional official delegates may be appointed by the Council later.

Members of the Institution desiring to attend the Conference unofficially should send in their names, with a remittance of £1 2s. 6d., to the Secretary of the Institution, who will obtain the necessary membership cards for them.

The Secretary of the Conference states that the holder of a card will be entitled to: (1) Attendance at the meetings, and participation in the discussions; (2) Two copies of each paper submitted to the Conference; (3) Participation in all entertainments and visits to works or excursions organized in connection with the Conference; (4) Special terms (if any) in connection with (3) above.

Informal Meetings.

The following Informal Meetings have been held :—

60TH INFORMAL MEETING (8TH DECEMBER, 1924).
Chairman: Mr. J. Coxon.
Lecture: "A Walk round the Pretoria Power Station" (delivered by Mr. G. M. Clark, M.A.).
Speakers: Messrs. B. A. Bent, A. F. Harmer, A. N. Aikman, W. A. Ritchie, W. L. E. Jones, A. G. Hilling, P. Dunsheath, O.B.E., W. Day, W. E. Rogers, V. N. Halliday, M. Whitgift and J. Coxon.

61ST INFORMAL MEETING (15TH DECEMBER, 1924).
Chairman: Mr. F. Pooley.
Subject of Discussion: "I.E.E. Wiring Regulations" (introduced by Mr. F. C. Raphael).

Speakers : Messrs. Ll. B. Atkinson, W. E. Rogers, H. J. Cash, W. R. Rawlings, K. A. Scott-Moncrieff, E. P. Hunter, H. T. Young, F. W. Purse, H. Marryat, W. E. Warrilow, J. G. C. Bacon, P. S. Davies, J. M. Donaldson and A. W. Tate; also F. Peake Sexton (written communication).

62ND INFORMAL MEETING (12TH JANUARY, 1925).

Chairman : Mr. P. Dunsheath, O.B.E.

Subject of Discussion : "Telephonic Development in Great Britain and in the United States" (introduced by Mr. W. Day).

Speakers : Messrs. A. F. Harmer, H. E. Morrish, J. R. Bedford, J. F. Shipley, R. J. Hines, S. M. Catterson, B. O. Anson, J. W. Wheeler, A. G. Hilling, E. S. Ritter, F. Pooley, H. J. H. Tabor and P. Dunsheath, O.B.E.

63RD INFORMAL MEETING (26TH JANUARY, 1925).

Chairman : Mr. A. F. Harmer.

Subject of Discussion : "The National Physical Laboratory and its Work" (introduced by Mr. S. W. Melsom).

Speakers : Messrs. P. Dunsheath, O.B.E., H. T. Young, J. R. Bedford, W. Day, C. F. Phillips, E. S. Ritter, F. Gill, C. L. Lipman and A. F. Harmer.

64TH INFORMAL MEETING (2ND FEBRUARY, 1925).

Chairman : Mr. F. Pooley.

The Chairman reported the death of Mr. C. H. Wordingham, C.B.E., Past-President, and as a mark of respect and to express their sympathy with the widow, the members stood for a few moments in silence.

Subject of Discussion : "The New I.E.E. Wiring Regulations" (further discussion).

Speakers : Messrs. J. Coxon, J. R. Bedford, W. A. Ritchie, A. F. Harmer, R. Grierson, E. S. Ritter, A. H. Allen, C. J. Lawrence, H. T. Young, F. C. Raphael, S. W. Melsom, L. J. Gooch, H. J. Cash, W. R. Rawlings and Ll. B. Atkinson.

Accessions to the Lending Library.

ALLMAND, A. J. The principles of applied electrochemistry. 2nd ed., revised and enlarged by the author and H. J. T. Ellingham. 8vo. 738 pp. *London,* 1924

BAKER, R. P. The preparation of reports: engineering, scientific, administrative. 8vo. 483 pp. *New York,* 1924

BALLANTINE, S. Radio telephony for amateurs. 2nd ed. 8vo. 296 pp. *London,* 1924

BISHOP, C. C. Electrical drafting and design. 8vo. 173 pp. *New York,* 1924

BRAGG, Sir W. H., *K.B.E., D.Sc., F.R.S.,* and BRAGG, W. L., *F.R.S.* X-rays and crystal structure. 4th ed. 8vo. 333 pp. *London,* 1924

BROWNLIE, D. Mechanical stoking. A practical treatise on the essentials of machine stoking, and the construction and operation of mechanical stokers. sm. 8vo. 244 pp. *London,* 1923

BURNHAM, T. H. Special steels. A concise treatise on the constitution, manufacture, working, heat treatment, and applications of alloy steels. Chiefly founded on the researches regarding alloy steels of Sir R. Hadfield, Bt., and with a foreword by him. sm. 8vo. 216 pp. *London,* 1923

CODD, M. A. Electric wiring diagrams for motor vehicles; embracing all the leading systems of lighting, starting and ignition for British, American and European motor vehicles. 8vo. 92 pp. *London,* 1924

COTTON, H. Electrical technology. A text-book covering the syllabus of the B.Sc. Engineering, A.M.I.E.E. and the National Certificate examinations in this subject. 8vo. 391 pp. *London,* 1924

CROFT, T. Alternating-current armature winding. 8vo. 361 pp. *New York,* 1924

—— Conduit wiring. 8vo. 468 pp. *New York,* 1924

—— Electrical machinery and control diagrams. 8vo. 317 pp. *New York,* 1924

—— Wiring for light and power. A detailed and fully illustrated commentary on the National Electrical Code. 4th ed. 8vo. 566 pp. *New York,* 1924

DAWES, C. L. Industrial electricity. part 1. 8vo. 385 pp. *New York,* 1924

DE BRUYNE, N. A. The electrolytic rectifier. Containing a chapter showing how to make and use a rectifier for charging accumulators from a.c. supply mains. sm. 8vo. 82 pp. *London,* 1924

DEL MAR, W. A. Electric cables; their design, manufacture and use. Lectures delivered in the Moore School of Electrical Engineering of the University of Pennsylvania, 1923-24. 8vo. 215 pp. *New York,* 1924

DOWSETT, H. M. Wireless telephony and broadcasting. 2 vol. la. 8vo. *London,* 1924

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 February–25 March, 1925:—

	£	s.	d.
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THE DESIGN OF ELECTRICAL PLANT, CONTROL GEAR AND CONNECTIONS FOR PROTECTION AGAINST SHOCK, FIRE AND FAULTS.

By H. W. Clothier, Member.

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Summary.

The risks to life and plant are set out.

Means for prevention are discussed in full and summarized in conclusion.

In the main an endeavour has been made to collate present practice and to ventilate some demands which are in a nebulous stage, including the duplication of components, the changing over of live circuits, the meaning of the breaking-capacity rating of circuit breakers, the use and effect of reactances, charging resistances and lightning arresters, and the best means of economy in switchgear without loss of safety.

In reviewing known automatic protective systems, stress is laid upon the importance of what has been termed, for the purpose of this paper, the "stability ratio." Stability takes precedence over sensitivity. In balanced automatic protective systems stability is jeopardized by influences, some of which are of recent discovery and have been brought to light by new conditions of service. They include the unbalancing effect of high-frequency oscillations on main lines, and interference by induction between the main line and the pilot line. Suitable remedies are available and have been applied.

The relation of interference with telephone service and fault occurrences on power supply systems provides a further argument in favour of good bonding, earthing the neutral and the instantaneous isolation of faults.

Mechanical consideration is given to the layout of switchgear and to the terminal construction of plant, and a diagrammatic illustration of the alternator main, field, and neutral connections is shown.

General Introduction.

The objects of this paper are to record the practice of enclosing conductors, and the automatic isolation of faults on electric power supply systems; also to consider the design from the point of view of protection to life and property, and the maintenance of continuity in the supply to the consumer. The dangers to "life" include shocks and burns; to "property," short-circuits and earth faults, explosion, fire or arcing to and from adjacent plant, and overloading of plant; and to "continuity of supply," the failure of plant and connections and incorrect sequence in manual operation.

To avoid shocks, it must be impossible for a person to make accidental contact with, or to come within arcing distance of, a live conductor. The ideal, then, is to enclose every conductor so as to render it inaccessible when alive. Burns may be due to direct contact or to arcs and flames spreading out from conductors and plant on the occurrence of faults or on the faulty operation of apparatus. This danger imposes the further condition for safety—that the enclosure must prevent the protrusion of hot gases and flame, and the discharge of inflammable gases in quantities likely to explode when mixed with the air in the switch-room.

The extent of the damage to plant and the consequent cost of repair increases with the duration of the fault disturbance. Prevention rests in perfecting the insulation, in using conductors and insulators of sufficient mechanical strength, and in placing them out of reach of any foreign substance. The duration of a fault may be restricted by their proper enclosure, which also will prevent the arc from spreading to adjacent plant. The prompt automatic isolation of the faulty section of plant by efficient discriminating systems of protection is a further essential in limiting the extent of injury to property. The explosion of gases and air within the building can best be avoided by suitable enclosure of the plant and switchgear.

Continuity of supply to any locality can only be assured by having duplicate ways, preferably entering from different routes as in the case of a ring main. The proper enclosure reduces the number of faults, but when they do occur they must be instantly isolated without interference with other sound parts or sections. The stability of sound parts during a heavy fault disturbance is of the utmost importance, and at the same time it is the most difficult feature to procure with certainty. It is frequently jeopardized by demands for relay settings which are unnecessarily sensitive and lower than need be, considering the fault-current amplitude which would be a real menace to the continuity of supply.

In order to reduce to a minimum the amount of work in operating supply systems of all sizes, the whole of the plant should be linked together in one common copper network. By this means the supply voltage to all consumers can be maintained throughout the day and night without a number of change-over and switching operations, and large fluctuations in load of an individual consumer are permissible without risk of undue variation in voltage to neighbouring consumers.

The human errors have been minimized by interlocking made to ensure correct sequence of operation, and by optical indication to show at a glance the condition of plant and connections. As time goes on, the further development of automatic service will doubtless remove many pitfalls from the path of operating engineers. The term "foolproof," sometimes applied to electrical apparatus, is a misnomer. "Mistake-proof" is better, because it must be remembered that rapid decisions have not infrequently to be made in the manual operation of plant, and also that even the most skilled persons are not always immune from error.

For many years the author has advocated the consis-

tent enclosure of all conductors and insulators, including a continuous earthed metal cover throughout the whole supply system, from the generators to the load, and even to lighting fittings. All portable plant and appliances should have the earth circuit to their metal covers continued through an earth conductor in the flexible cable. In the supply to coal-cutters and conveyers in mines it is a recommended practice * to surround the outer insulation of the flexible cable (" trailer ") with an earthed sheath of copper braiding in addition to the compulsory earth conductor, thus continuing the metal covering over flexible cables also.

Carried to a logical conclusion, overhead lines would be replaced by underground cables, which are much to be preferred on all counts with one unfortunate exception, the initial cost.

" Metal-enclosed " is a term used to denote that type of construction in which all conductors and insulators are totally enclosed within an earthed metal casing.

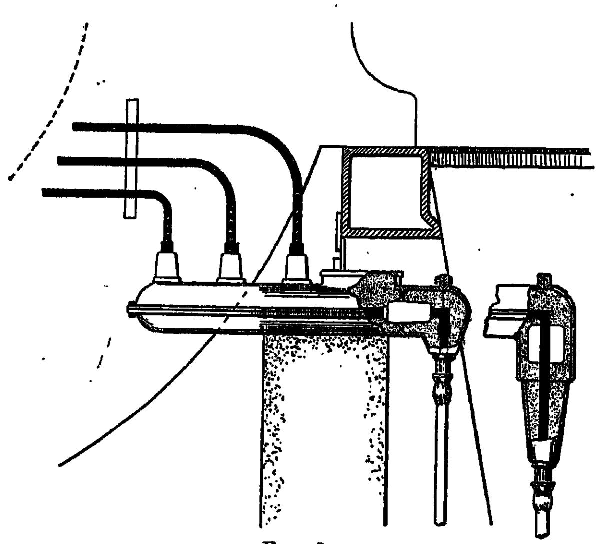


Fig. 1.

" Metal-clad " has been used in preference to " ironclad," " armour-clad," etc., to denote that type of construction in which conductors and insulators, either singly or in groups, are contained and surrounded with metal covers fitting over them like a garment. Thus the several component parts are separately covered and are capable of assembly in relation to each other to form a self-supporting and self-contained unit.

Construction.

Metals used for enclosure.—Metal for casings must be so disposed that the magnetic circuits are broken where necessary to avoid heating by hysteresis and eddy currents. Whilst non-magnetic metal is necessary to sheath a separate single-phase conductor, much larger currents may be carried by conductors sheathed in ordinary iron or steel if grouped so that the resultant flux due to their respective magnetic fields is negligible. When conductors for very large currents are to be metal-clad, the grouping of the several conductors may not sufficiently reduce the resultant magnetic flux; in this case one or both sides of the sheathing must be made of non-magnetic material such as cast gunmetal, brass, or aluminium, according to its situation on the gear. Non-magnetic cast iron has also been found to have the required reluctance and also has the further advantage of high resistance to eddy currents. Non-magnetic steel has occasionally been used in some places, particularly where cast iron is unsuitable owing to its liability to fracture. In other cases copper is used for its toughness, and advantage is taken of its high conductivity which enables it to carry eddy currents without excessive heating. When the clearance between the conductors, insulation and enclosure is not filled in, the gear is described as " air-insulated." When it is filled in with compound it is described as " solid," and when with oil, " oil-immersed."

Metal covering on plant.—The principle of metal enclosure has been well evolved in the general designs of alternators, motors, and other rotating plant. Electrical design dictates that the windings shall be embedded in iron, and ordinary robustness that the projecting ends

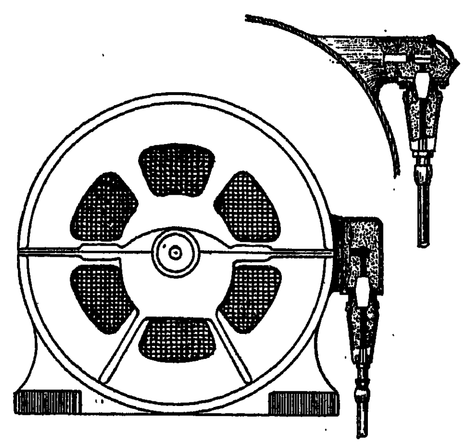


Fig 2.

of the windings shall be protected by a metal end-cover. The entire framework must also be earthed to avoid the risk of shock to attendants. More often than not, however, the proper finishing off of the metal enclosure has been neglected at a most critical place, namely, at the terminal ends of the stator windings. A solid type of metal-clad fitting, providing at the same time a sealing box for the cables, is appropriate at this position. A typical arrangement for a large alternator is shown in Fig. 1.*

Terminal and cable-sealing boxes for smaller machines and motors have been made in various shapes and sizes, and are now a subject for standardization. One method is illustrated in Fig. 2. During the past three or four years power transformers have been subjected to the treatment of enclosure. The demand for economy has led to placing transformers out of doors, and this has been an extra inducement to the complete metal enclosure. A typical pair of sealing end-boxes is shown in Fig. 3. The insulation has required special

* See Coal Mines Act, Explanatory Memorandum (1921), page 52.

* Woodhouse and Melton, Yorkshire Electric Power Co.

research owing to the high temperatures at which it is permissible to run this form of plant on load. Moreover, transformer oil is very penetrating. Joints between the insulator and the metal covering must hold the oil without any creepage, notwithstanding the contraction and expansion of different adjacent materials throughout a great range of temperatures varying from below freezing point to 95° C., not taking into account the extra heat due to the sun's rays. The design shown includes a vitreous porcelain insulator with a surface ground perfectly true and flat and clamped hard upon an oil-proof insertion washer over a machined metal seating. This has given better results than many others tried. The metal enclosure also has presented problems peculiar to this plant. Generally the conductors are enclosed therefore, the principal requisite for complete and continuous enclosure consists in a carefully designed connection between the ends of the metal-clad cable and the metal enclosure. Although often in British practice, and almost invariably in American and Continental practice, the intervening switchgear conductors have provided the biggest obstacle, extensive British development and experience in metal-enclosed switchgear are now available to surmount this. This includes " cubicle," " truck," and " metal-clad " types. The two former have usually been " air-insulated " types, and the latter a " solid " type. The air-insulated types are a half-way measure; the sets of conductors are covered by a sheet-steel enclosure, but there is not the distinct inaccessibility of every conductor throughout its whole

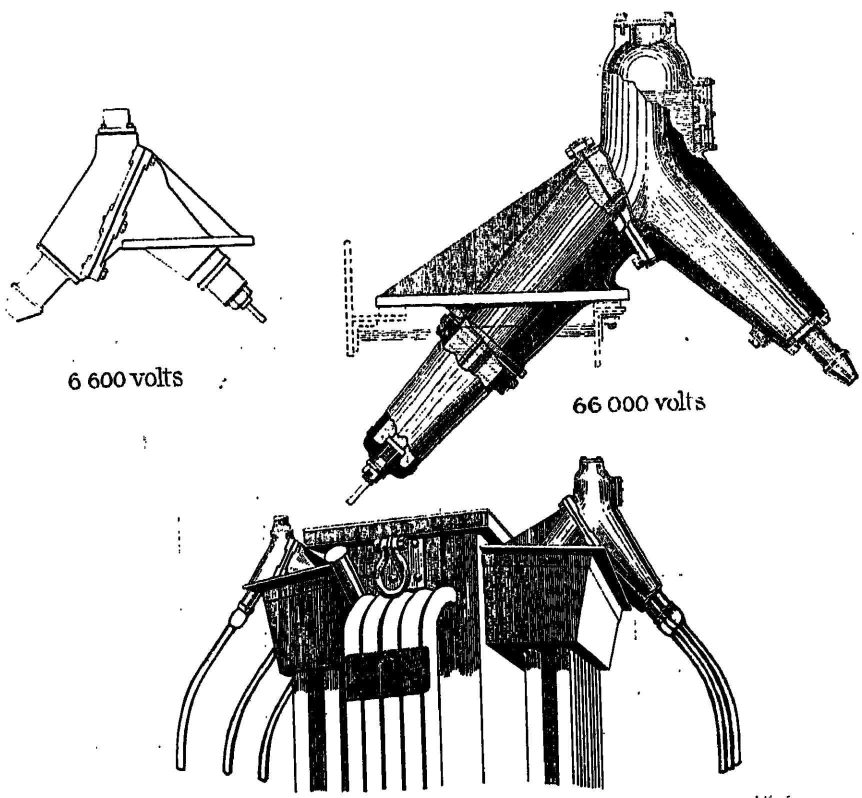


FIG. 3.

separately, and for heavy currents must be non-magnetic. Conservator tanks maintain a slight pressure of oil from within, and it has not been so simple as might at first be thought to procure suitable castings to withstand the specified oil pressure-test of 15 to 30 lb. per sq. in. without the slightest trace of oil leakage.

The enclosure of reactances when immersed in oil tanks can be dealt with in the same way as that of transformers. Reactances made in the form of coils of lead-covered cables embedded in a concrete block with ends finishing in metal terminal boxes are truly metal-clad, and as such are very suitable for the purposes under consideration, as the apparatus is virtually a coil of metal-clad cable.* Throughout the layout of plant,

* Beard.

length that is afforded in the solid types by the compound filling.

Metal-clad switchgear construction.—Metal-clad " draw-out " switchgear has been made in three general classes as follows :—

(1) Horizontal isolation (Fig. 4).*
(2) Upward isolation (Fig. 5).*
(3) Downward isolation (Fig. 6).†

Great care has been exercised in the design in order to prevent accidental access to the live socket contacts within the isolating orifice. In the horizontal draw-out gear they are deeply recessed and the orifice is automatically closed over with a door when the switch is withdrawn. Similar locking-off doors are applicable to

* The author. † Erskine, Heap.

the upward isolation draw-out types, but in addition this plane for withdrawal permits the oil immersion of the isolating socket contacts.*

Duplication of components.—In the general layout of switchgear the amount of duplication should be

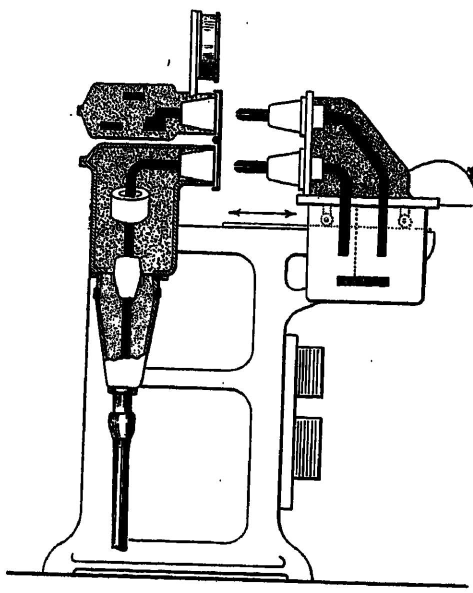


FIG. 4.†

governed by the liability to breakdown. Given absolute immunity from breakdown, the simplest arrangement solely required for the control, protection and indication should be adopted. The metal-clad enclosure of all conductors certainly does reduce the possible extent of switchgear breakdowns, thanks to its unit form and to

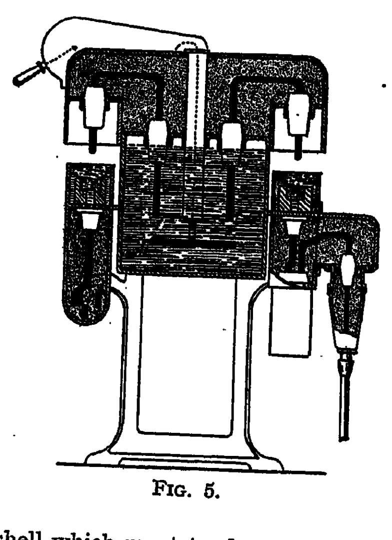


FIG. 5.

the metal shell which must tend to localize the disturbance and prevents the spread of arcing. It is better economy to increase the initial expenditure in obtaining quality and strength of parts, thus tending to make them immune from failure, than to duplicate such parts ;

* The author.

† Figs. 4, 5 and 6 are diagrammatic of classes only and are not intended to show details of any particular manufacture. Busbars are shown compound filled (Highfield).

for instance, one good circuit breaker is better than two of inferior quality—it engages less attention and maintenance, to say nothing of the saving in initial outlay for housing.

The draw-out feature has been shown to be a good substitute for the duplication of circuit breakers, in so far as it furnishes a ready means of inspection in safety and of the substitution of one circuit breaker for another at short notice.

On a few occasions during the life of the plant the duplication of busbars may be advantageous. For example :—

(1) When running up a new or doubtful machine on an independent circuit or test-circuit.
(2) When making extensions one bar may be made dead at a time.
(3) For cleaning purposes.
(4) In case of breakdown of switchgear.

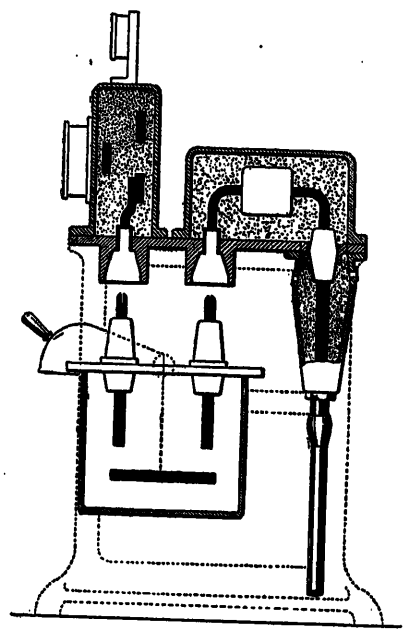


FIG. 6.

One of the objects of the metal-clad form is to eliminate items (3) and (4). The complete enclosure of all insulators does save cleaning operations, and the chances of breakdown are certainly remote if due care is taken in the selection of gear suitable for the most severe conditions of service.

Duplicate busbars and changing circuits.—The changeover from one circuit to another is always more or less risky, according to circumstances of the load and the design of the apparatus. Many serious accidents and shut-downs have occurred due to the faulty opening of busbar selector switches whilst carrying load on open-type switchgear. One large power supply station was shut down three times in one year on this account, and so, from the earliest* metal-clad power station switchgear, care was taken to remove this danger by suitable designs and interlocking, making it impossible to change

* Stepney and Neepsend.

circuits over when on load. To accomplish this the hood of the circuit breaker was fitted with two sets of plug sockets, corresponding to the top and bottom busbars, and one set of plugs. Access to change-over plugs can only be obtained by first withdrawing the circuit breaker carriage (see Figs. 8 and 14). The change-over fittings are thus safe, and it is impossible to change over when load is passing through the circuit. A device either hand-operated or automatic, interlocked with synchronizing connections and auxiliary switches, gives

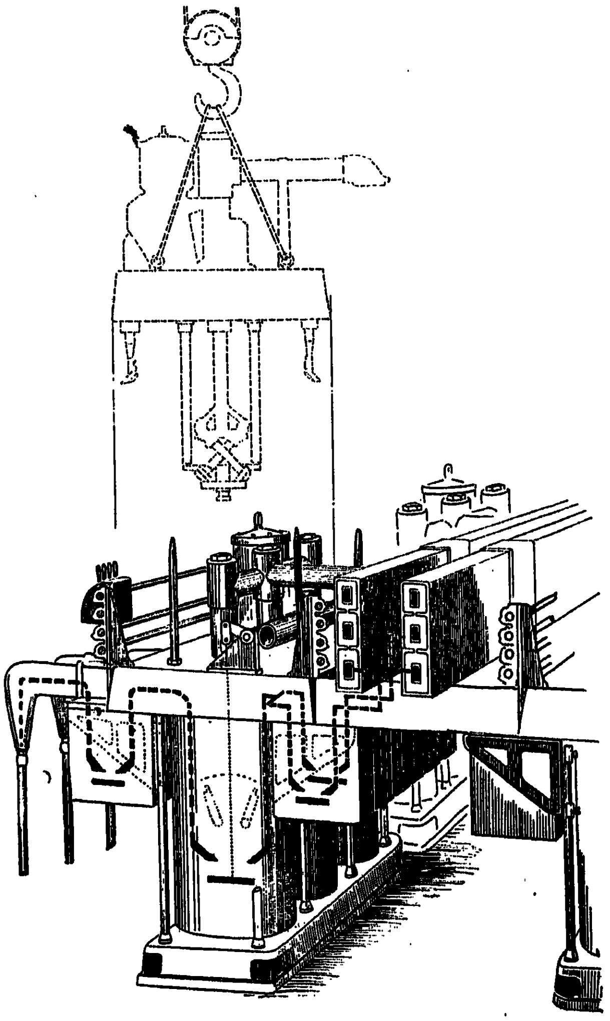


FIG. 7.

direct and remote, " top " or " bottom " busbar indication.

To be able to make the change-over without having first to open the circuit on the oil circuit breaker has recently been claimed to be an advantage, and several methods have been investigated. One proposal * consists of enlarging the hood (see Fig. 9) and withdrawing the plugs from the front of the switch, interlocks being provided that will allow both sets of plugs to be " in " at the same time when the bars are in parallel. Care must be taken that no portion of the live plug is accessible during the process of withdrawal. Another plan involves the use of two circuit breakers suitably interlocked (Fig. 10). A modification of this practice is to put the two circuit breakers into one double-contact circuit breaker (Fig. 11).* Another proposal is to substitute for the plugs a set of change-over switches immersed in oil or a semi-fluid insulating compound within the hoods on the circuit breaker (Fig. 12).

* Christianson.

The interlock must in any case be so arranged that

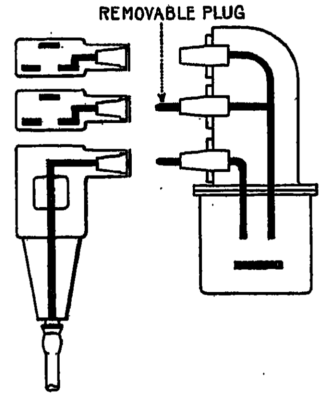


FIG. 8.

electrical contact between the busbars is never made on the change-over device unless the busbars are in synchronism. That is to say, the coupling switch joining the busbars must be closed and cannot be opened until the change-over has been completed. Sometimes a coupling switch must be installed only for this purpose, involving considerable extra expense. To open the

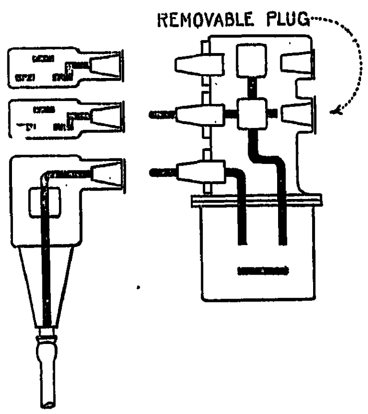


FIG. 9.

circuit before changing over is the safe way and is more simple in design. The need for changing over whilst the circuit is alive is often more imaginary than real. It is necessary in either case to arrange the circuits on the system so that any one of them can be made dead without interfering with the continuity of supply. For example, a generator can always be disconnected for a short time when others are running, and the layout

* Ferguson and Pailin.

of feeders also, if made with parallel feeders or ring mains, provides for the disconnection of any feeder at short notice. If only for the proper maintenance of switchgear these facilities are required, one reason being that circuit breakers can be periodically tried to ensure that they trip correctly on the occurrence of faults. Moreover, it must be so in practice because at any time a generator or feeder might be cut out automatically —an incident which should not interrupt supply. Rapid and hasty changing-over during times of emer-

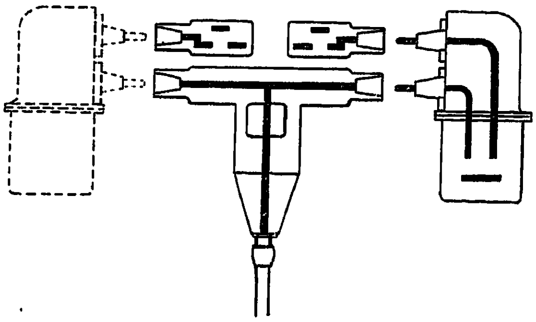


FIG. 10.

gency inevitably leads to errors and consequent interruption of supply. In one type of upward isolation draw-out gear, oil-immersed busbar selector switches are included in the fixed portion (Fig. 7). There is less difficulty where selector switches are used, as in this form of gear, in changing over on the live circuit, but it is still best, in order to simplify the design of interlocks and to limit the operating functions, to make it impossible to move these selector switches whilst the circuit is closed.

Separation of phases.—The separate phase enclosure

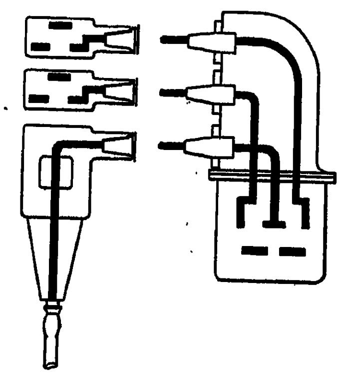


FIG. 11.

in metal-clad switchgear is, as a general rule, only adopted where circumstances of heavy duty and comparatively high voltage occur or combine to make it advisable. These conditions certainly exist in the case of capital stations and in extra-high-voltage networks of large kVA capacity, but present experience indicates that the multi-phase enclosure of busbars, instrument transformers and connections sealed in compound is quite sufficient for power stations in which the aggregate full load is below 100 000 kW, or in which the pressure is below 40 000–50 000 volts. The practice in this respect is somewhat analogous to the respective use of 3-core or single-core cables.

The likelihood of an internal fault is remote, but should one occur the arc cannot be long or sustained, because it is confined to the earthed metal in its own

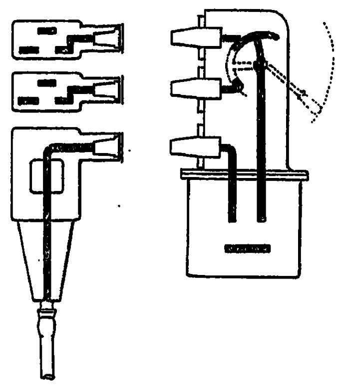


FIG. 12.

close vicinity. It is not so with the cellular switchgear in which there are open conductors separated from earth by large air spaces. In some of the largest stations in the world the phase separation has been carried out to the extent of providing what is virtually a separate building for each phase. Experience has shown that even with this extreme precaution a fault can spread from one phase to another and—even more serious from the point of view of continuity of supply—from one circuit to another. At least one incident is on record where the entire switchgear was destroyed

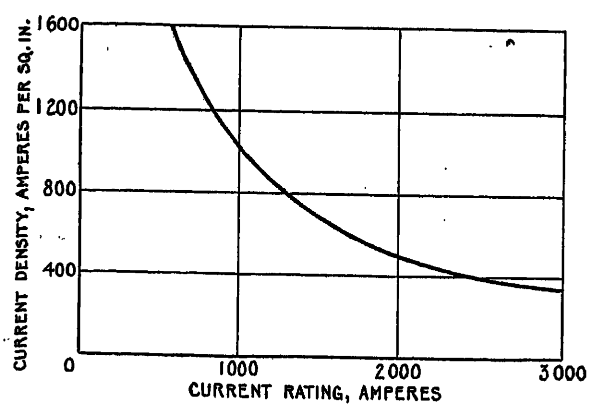


FIG. 13.

irretrievably by fire caused and sustained by an arc having a resistance too high to cut out the generators, and there are many cases where arcs have spread over two or more panels, necessitating a complete shut-down of the power station.

An example of complete phase separation with metal-clad switchgear is shown in Fig. 7.* The busbar

* First design: Dalmarnock (1917), Carville (1917), Nechells (1919). Gregory and Electrical Improvements, Ltd.

chamber is divided into three compartments, earthed metal surrounding each phase. The isolating switches, circuit breaker, current transformer and single-phase potential transformer, and all connections down to the cable dividing-box, are in separate phase enclosures. The principle may be extended by using single cables for generator and transformer leads.

Busbars.—The simpler the busbar system the better. The only connections to them should be those which pass through the main oil circuit breakers which, when drawn out entirely, isolate all other conductors in the panel from the busbars. The design allows for filling in all busbar sections at the factory, and afterwards a pressure test of three times the line voltage between phases and between all phases in turn and earth is carried out. Unfortunately, the compound filling is a poor conductor of heat and, therefore, current densities must be low, particularly so at the heavy current ratings with the ordinary form of construction. Fig. 13 is an approximate curve for the safe rating, and shows the relation of current rating to current density.

The magnetic forces which set up mechanical stresses between conductors during the passage of heavy "through" fault currents, present no difficulty to the metal enclosure and compound filling. On the contrary, cell gear with its long open-type conductors must have insulating supports additional to those required for natural construction and connections. These are not required on solid metal-clad gear, because not only are the centres and general dimensions more compact and the conductors shorter, but the compound in which the conductors are embedded acts as a solid buffer to movement under impulsive stress.

Circuit Breakers.

Circuit breaker enclosure and breaking capacity.—The enclosure of the circuit breaker is a large factor in determining the breaking capacity. The majority of circuit-breaking failures have been the result of weakness in the tanks and top plates. The predominant feature is the relation of the arc energy to the impulse pressure on the walls, top and bottom of the oil-switch enclosure.

The impulse pressure on the sides of the tank varies roughly as the inverse square of the distance from the arc, and this factor enters into the determination of the most economic and effective dimensions of the tank, the minimum dimensions being controlled by the clearances necessary for the working voltage. In the case of metal-clad gear in ordinary industrial service the circuit breaker has been more economically and conveniently arranged in one tank than in three separate tanks. Metal divisions inside the tank surrounding three sides of the sparking contacts, for a breaking capacity above 100 000 kVA, eliminate the risks of arcing between phases, in addition to strengthening the tank (Fig. 15).

Vent pipes can never be large enough to give adequate relief to local pressures established by the arc within the tank. Moreover, open vents throw large quantities of oil. On the other hand, as some outlet is necessary to allow for the exhaust of the gases and smoke which are products of the arc, the practice of a baffled vent has been evolved. To prevent fouling the atmosphere in the switch-room it is best to conduct the vent pipes to the outside of the building. An open area in the centre of the building (see Fig. 20) is useful for this purpose.*

Reduction of arc energy.—Various methods have been advanced to limit the amount of arc energy and the resultant stress upon the enclosure. The most common has been to speed up all movements after the relays have set them in operation, on the principle that the duration of the arc must be reduced to a minimum. A reasonably high velocity after the separation of the contacts at the first zero point on the current wave, with a short break, has been aimed at in preference to a long break.

Another method, which incidentally also increases the velocity of the break, is to employ a number of breaks in series, but any increase beyond two will lead to complication in design and consequent weakness or increased expense to maintain the same standard of insulation in view of the additional parts.

A further method has attracted much attention. The arcing contacts are enclosed in a steel cylinder called an "explosion pot." It has been claimed that this design takes advantage of the explosion to speed up the break, and, as the worst of the impulse pressure is taken within the pot, the walls of the circuit breaker need only be strong enough to contain the oil.† Whilst this may be an excellent means of strengthening existing weak circuit breakers, it does not allow for accidents in the working of the explosion pot. At some time or other the arc or gas explosion may occur outside the pot, in which event the ultimate safeguard is the strong external enclosure. Then the solution will be more expensive and, in the long run, really no more efficient than a circuit breaker with rational arcing contacts.

The simplest construction of current-carrying and arcing contacts includes one or, at the most, two breaks, spring loading for increasing the natural acceleration due to gravity, and a large volume of oil. Incidentally the oil volume provides ample clearance for insulation, particularly along the insulating surfaces between the contacts and the top plate, and a good head of oil above the point of separation of the arcing contacts. The whole is enclosed in boiler-plate tanks and a steel top plate is attached, together with correspondingly strong studs or bolts and flameproof flanges. This construction has been applied to reduce the arc energy to an economic minimum and to provide sufficient strength of enclosure to withstand the impulse pressure arising therefrom.

A typical design of circuit breaker embodying the features advocated is shown in Figs. 14 and 15. This has been used on generating plant of 60 000 kW with 10 per cent reactance. The tank is capable of withstanding without permanent distortion a sustained hydraulic pressure test of 350 lb. per sq. in., which corresponds to an impulse pressure possibly 10 times greater.

Rated breaking capacity of circuit breakers.—Some advance has been made in recent years on an expression of the breaking capacity. The B.E.S.A. definition ‡ is :—" The breaking capacity of an oil immersed circuit breaker is the maximum kVA which the circuit

* Colenso power station.
† Hilliard (U.S.A.). See also Bernard Price: *Transactions of the First World Power Conference*, 1924.
‡ B.S.S. No. 116—1923.

breaker will break, under prescribed conditions, at stated intervals, a specified number of times. The value of the maximum kVA is the product of the rated working voltage in kilovolts, and the actual current at the time of separation of the contacts, multiplied by 1, 1·73 or 2 for single-phase, three-phase, or two-phase systems respectively." The specification explains fully that the current on a severe short-circuit will reach temporarily a high value but that " due much room for speculation as to what the kVA rating of any circuit breaker really means in relation to satisfactory service on a specific size of plant. Is the 10 000-kVA power station to have 60 000-kVA or 200 000-kVA circuit breakers ?

Performances of circuit breakers have had in the main to be gauged from experiences in places where they have been overloaded under short-circuit conditions. In such situations comparatively small circuit breakers

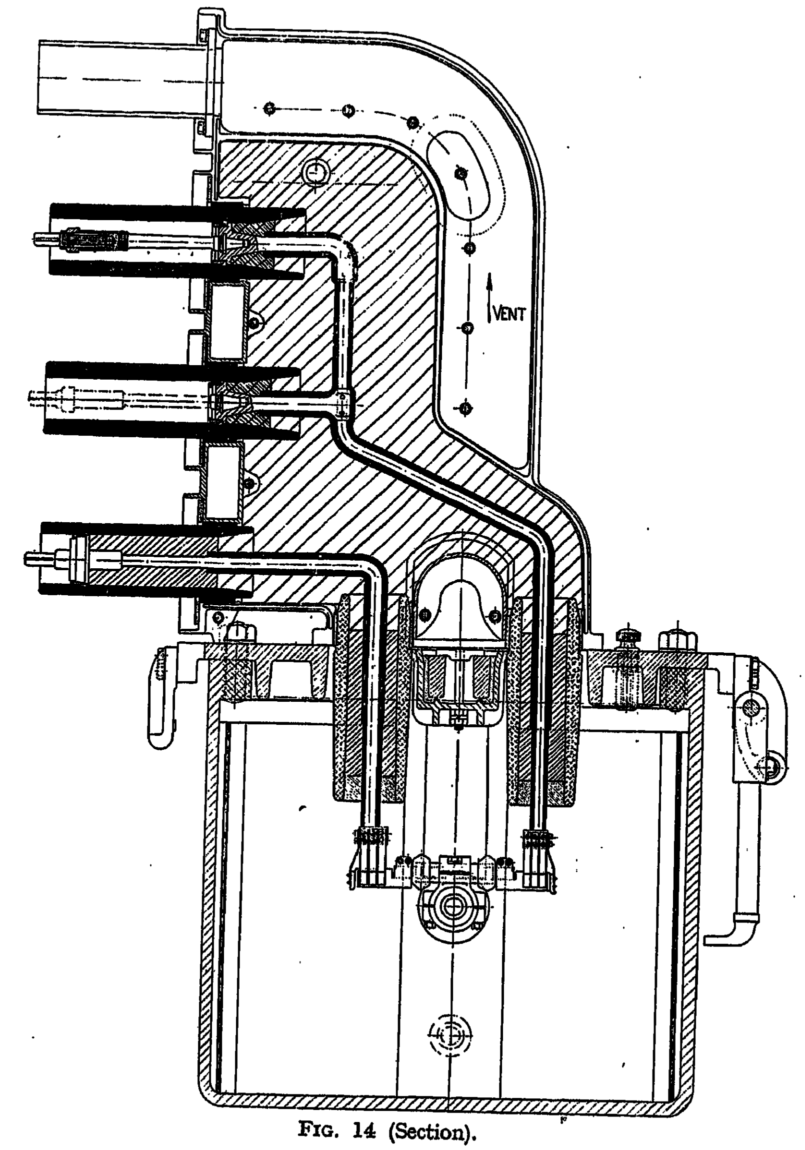


FIG. 14 (Section).

account " should be taken of reduction in the current to be broken as affected by the time characteristic of the circuit breaker and relays. As an example, with this easement a generator circuit breaker may be rated at six times the total kVA load of the generator (10 per cent reactance on short-circuit), although it is admitted that under a combination of the worst conditions on the same circuit as much as 20 times the current may have to be broken. Between these two values there is have satisfactorily cleared faults of much larger value than that for which they were originally intended, but when fixing commercial ratings due margin for safety had to be made to cover the unfavourable hazards also met with in practice. For example, a switch of the dimensions indicated in Fig. 16 has served at a colliery, which made rapid electrical developments, in places where the short-circuit was not less than 60 000 kVA. If commercial ratings were based solely upon such

experiences, the manufacturer, acting upon the B.E.S.A. specification, might advance this circuit breaker for use on plant of an aggregate full-load capacity and 10 per cent internal reactance of 10 000 kVA.

By way of comparison the corresponding sizes of actual commercial ratings in use to-day are indicated in Fig. 17. It will be seen that these larger circuit breakers range from 25 000 to 150 000 kVA breaking capacity.

According to whether the plant is to be one-sixth of

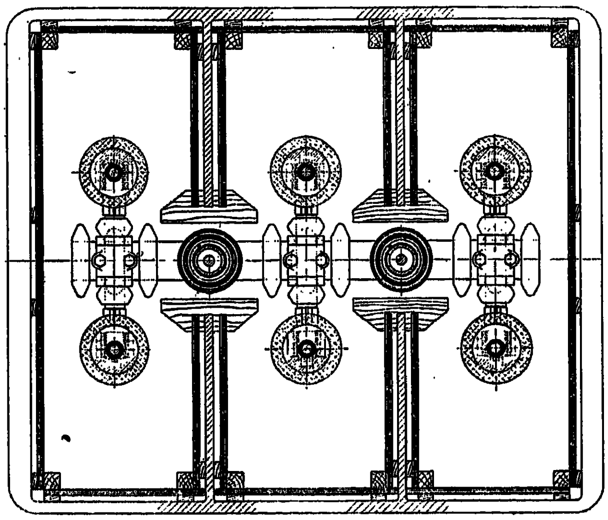


FIG. 15 (Plan).

this (as recommended by the B.E.S.A.) or one-tenth (as preferred by the author), these circuit breakers would be used on plant aggregating 4 166 to 25 000 kVA or 2 500 to 15 000 kVA respectively.

The introduction of reactance, whilst reducing the current and therefore the destructive mechanical forces on all parts of the system, does not necessarily reduce the arc energy with which the circuit breakers have to

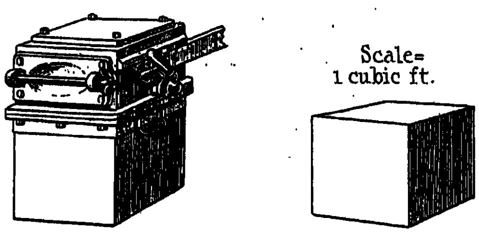


FIG. 16.

deal in clearing short-circuits from the system. In fact, in some cases the stress experienced on the circuit breaker has been actually greater due to the reactance, notwithstanding the reduced current value.

It has also to be borne in mind that the sparking contacts may separate at any part of the fault transient. For example, if the fault (it may be a high-resistance fault or a fault to earth culminating in a dead short-circuit) starts at A (Fig. 18), the sparking contacts may separate at any point from B onwards. At the worst,

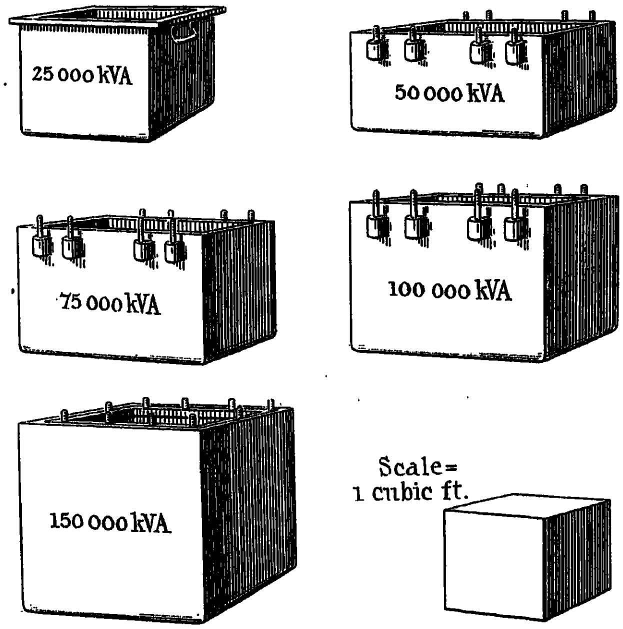


FIG. 17.

in rare cases it might be at C, when the breaking capacity is the maximum, viz. 20 times full load. If it is an instantaneous short-circuit the contacts would separate

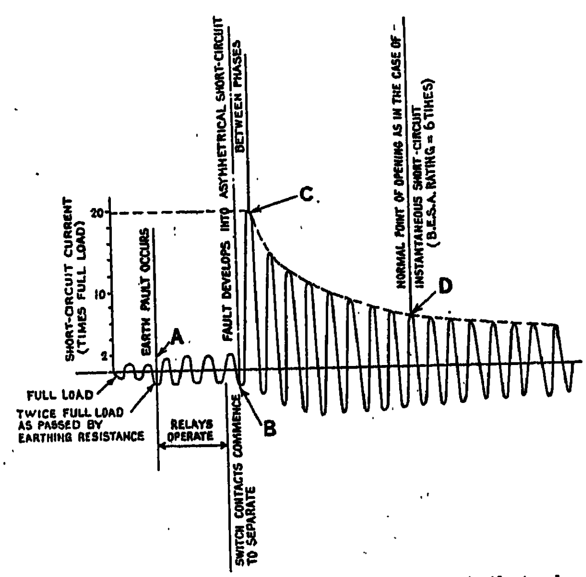


FIG. 18.—Curve illustrating maximum current that circuit breaker should clear.

in most cases about D, where the kVA on the B.E.S.A. basis would be six times full load.

In any case the circuit breaker must be designed to

withstand the mechanical forces and impulses given by the current at C. It should also break circuit at this stage at least without danger to persons or neighbouring plant, although it might in such exceptional circumstances require some attention before being put into service again. Moreover, the specification recommends that as the current to be broken "is limited by the reactances and resistances in circuit," the rating of the circuit breaker may be reduced in proportion. This seems to be in conflict with the experience that in circuits carrying equal current additional reactance increases the arc energy, and so at present the breaking capacity may not truly represent the work that the circuit breaker has to do in breaking the circuit.

Of course the way to rate any article is to base its performance upon some unalterable standard. It would therefore be a better guide, in stating the breaking-capacity rating of a switch, to qualify it by stating the basis in terms of generating-plant output and reactance on short-circuit.

burning of contacts, or other forms of permanent injury." Any circuit breaker should be capable of carrying the maximum "through" current possible in its situation on the system for at least 1 second in order to provide a margin for safety in the duration of a through short-circuit for ½ second.

For power station service a high "through" rating current is required of not less than 100 times the normal current-rating of the generator switchgear panels, assuming not more than 10 generators of 10 per cent reactance. At such ratings the conductors must all be so arranged that the magnetic forces improve the current-carrying capacity of the contact surfaces. This rating has sometimes been called the "thermal rating," but as there are other deforming causes than temperature, for instance strains on conductors due to magnetic causes, the thermal characteristic is not the only one and the term "through" rating would appear to be more expressive.

Charging resistances on circuit breaker contacts.—There is a considerable element of doubt as to the utility of charging resistances contained within circuit breakers and carried on the moving contact for the purpose of limiting the current-rush on switching-in power transformers and motor armatures. It is now generally recognized that their use for switching-in cables is unnecessary. All plant should be capable of withstanding the stress of switching without their use, as the stresses to which the plant may be subject are not always controlled by the charging resistance, since there are conditions of charge which occur in circumstances other than the closing of the individual circuits—for example, the re-establishment of the supply after a momentary cessation occurring during the clearance of a fault on another part of the system. Certainly the circuit breaker is greatly simplified by the elimination of the charging resistance.

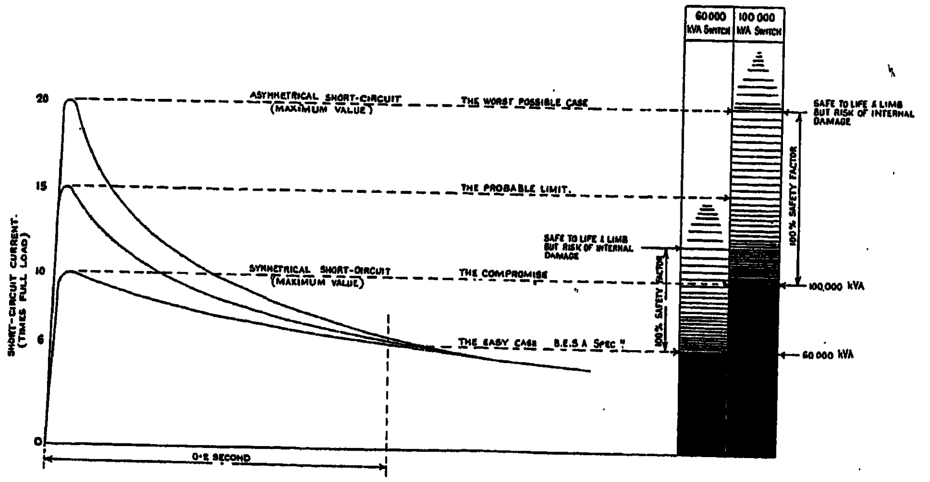


FIG. 19.

Shaded portion shows encroachment on safety factor; 10 000-kVA plant assumed.

A suggested compromise is to rate circuit breakers as being perfectly efficient at the maximum symmetrical current, viz. 10 times the aggregate full load, but admitting encroachment upon the design safety-factor at the exceptional asymmetrical current up to 20 times full load (see Fig. 19). If this were the understanding between the buyer and the maker it would only remain, in selecting the required size of breaker, to make allowance for any deviations from the standard circuit in inductance, resistance and capacitance, appertaining to the position and circumstances of the circuit on the system. A generator circuit with more inductance than the 10 per cent internal reactance on short-circuit may require greater breaking capacity, and a distant non-inductive circuit less than the standard, for equal short-circuit currents. The exact adjustment is a matter for experience and research.

"Through" rating of a circuit breaker.—The "through" rating of a circuit breaker may be defined as "the maximum current that the circuit breaker will carry during the transition period of a fault current without deformation of any parts of the circuit breaker,

LAYOUT.

Layout of busbars.—The simple layout for power station service, shown in Fig. 20, provides for parallel

running in sections, any of which may be completely isolated from or coupled to a common duplicate busbar. The dotted lines represent the outline of the switch-house building. The inside, open area provides light and an outlet for the vent pipes.

Reactances.—Reactance, if necessary, may be connected either in star fashion (Fig. 21) or in parallel with the busbar section switches (Fig. 22). There is but little to choose between these two systems from the point of view of the cost of a reactance for equal service. These diagrams lead one to suggest that on an all-solid system where the duplicate busbar is rarely, if ever, used, it might be made to serve the dual purpose of "hospital" busbar and reactance tie busbar, thus saving the initial and upkeep expense of the separate reactance plug-gear and busbar.

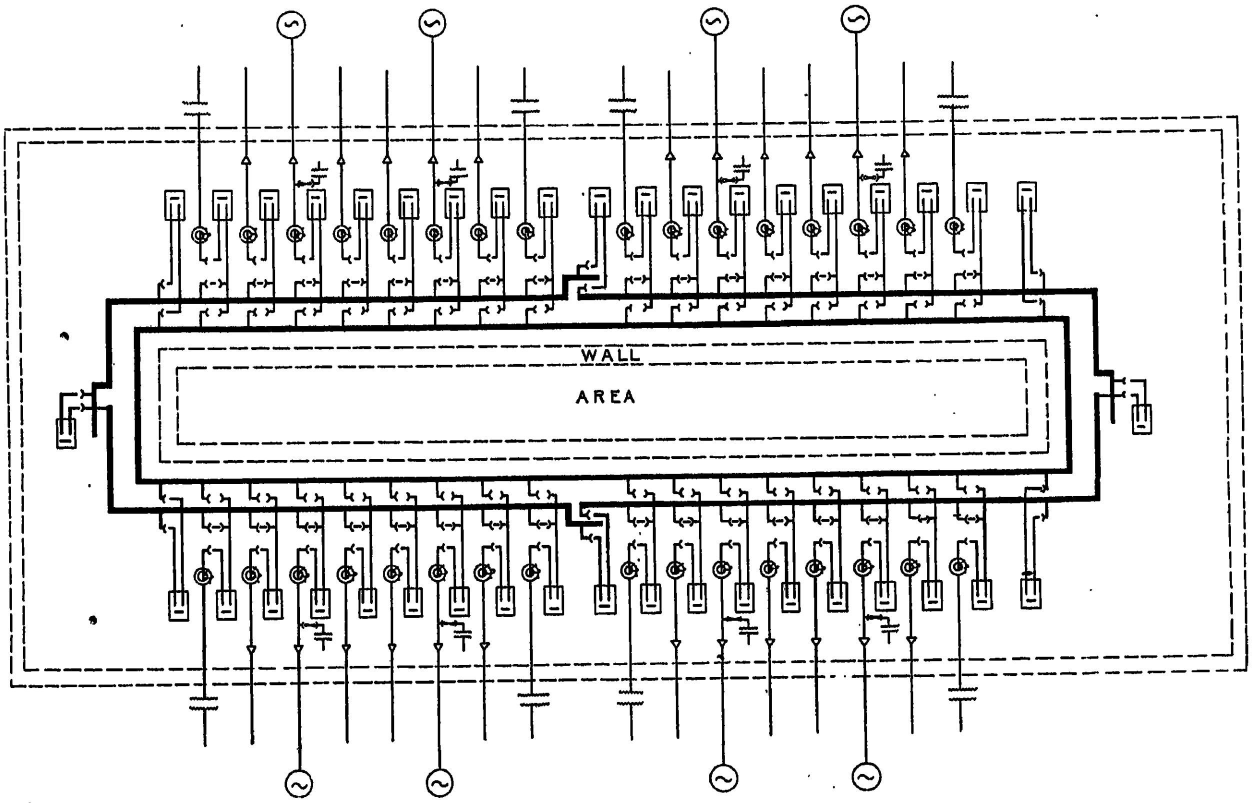


Fig. 20.

The use of a reactance is apt to complicate the layout of the gear and the operating conditions. For example, the effect of reactance between busbar sections may be nullified by an interconnection on the network of a ring main in parallel with the reactance.

Much care must be exercised in determining the values and location of reactances, otherwise the resultant complication due to voltage variation may be troublesome from an operating standpoint and militate against some of the advantages to be derived from the complete parallel running of the network on a large system.

Economy in layout.—It is preferable to employ, throughout the system, circuit breakers competent to act without artificial inductance, that is, other than that inherent in the design of the cables, transformers and generators. The economy in being able to lay out and run the network without having to think when, or when not, to put in reactances is an item which can be balanced against the possible extra initial cost of the switchgear. Moreover, as stated above, inductance in the fault circuit, although it reduces the fault current and the mechanical forces due to such currents, does not necessarily reduce to the same degree the energy dissipated in the arc and consequently the performance of the circuit breaker. This must not be overlooked when contemplating the use of reactances for the sole purpose of restricting the arc energy in circuit breakers when operating under short-circuit conditions. Single-phase faults to earth might be reduced to comparatively low values by the insertion of resistances between the neutral point of the generators and earth, but even in this case there is the risk of another earth fault occurring simultaneously on a different phase. This condition would be nearly as severe on the circuit breakers as an unlimited fault to earth.

Other Components.

Current transformers.—Considerations of shock risk must include the possibility of high secondary voltage due to an accidental opening of the secondary circuit. This condition also carries with it the risk of breakdown

due to excessive temperature caused by hysteresis in the iron core. Both these risks can be reduced, if not altogether eliminated, by suitable design of electrical characteristics. The impressed electromotive force should be strictly curtailed by reducing the number of primary turns to a minimum. The single-turn (bar type) primary has much in its favour, and, whenever possible, instruments should be designed to suit. In some cases it pays to sacrifice over-exacting accuracy to safety and convenience in maintenance and operation. A full-load secondary current of 5 amperes is preferable to one of 1 ampere because, as the secondary voltage varies inversely with the current, the difference might be that between discomfort and danger when touching with the hand the terminal of a relay at such a time that the secondary is open-circuited and a large primary "through" current is flowing. Delicate fault-settings of relays are sometimes attempted by the use of large current transformers, whereas coarser settings would give almost equivalent protection to the system with much greater security. The single-turn primary for current-transformer working with instruments on supply systems of 20 000 volts is very desirable. At 33 000 volts and over it is more so, because a primary winding

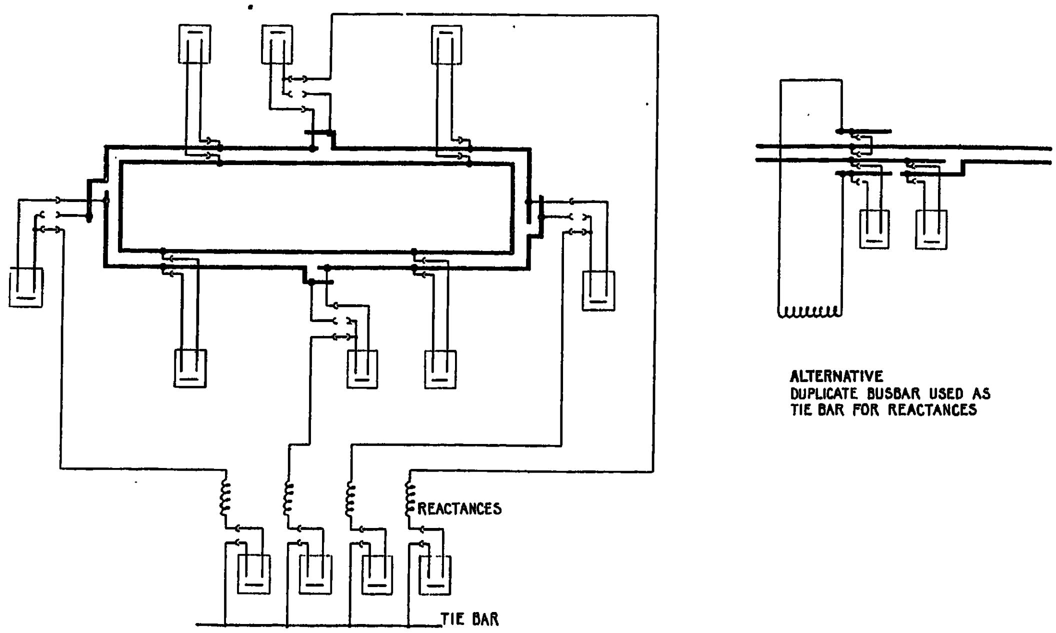


FIG. 21.

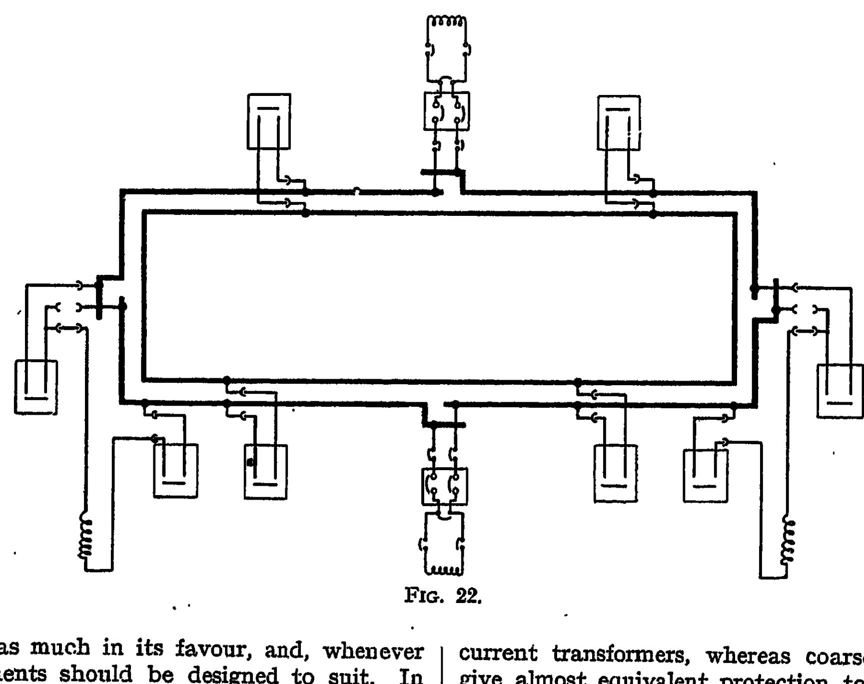


FIG. 22.

of two turns or more increases the dimensions and manufacturing difficulties altogether out of proportion to the difference in the number of turns. For instance, the single-turn transformer may have the primary in the form of a lead-covered cable or a copper bar with a solid insulator threaded through its core, whereas the transformer with two turns must have one convolution over the core. Unless a large difference is allowed in the cost or in the space occupied, the choice in insulation lies between a metal-clad conductor or a sound vitreous body like a straight porcelain bush and a flexible fibrous material moulded or wound on cloth or paper; this latter alternative must be very well done to be anything like so durable.

Insulation durability.—The author has found security in a high standard of pressure tests on individual parts and assembled gear. The failure of insulation on switchgear in service is so serious that even at an increased initial cost it is economical in the long run to have a large margin between the normal voltage and the breakdown voltage. It is, however, also essential that the test pressure shall be well below the breakdown voltage in order to safeguard against the possibility of over-straining the insulation in the process of pressure

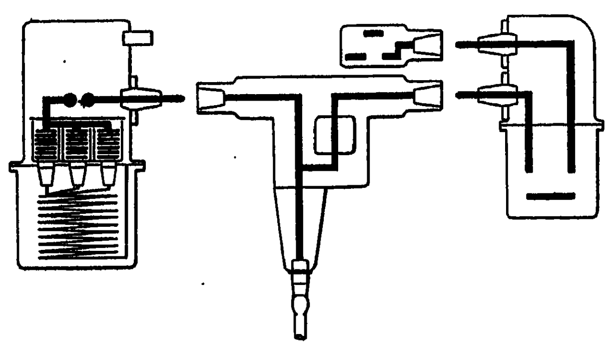


FIG. 23.

testing. Up to 20 000 volts a standard of design for each insulator to break down by flash-over at not less than 4 to 5, and by puncture at not less than 6 to 7, times the line voltage at normal frequency in a "type test" of 1 minute's duration, at its maximum working temperature, has allowed commercial pressure tests on assembled gear of 3 times the line voltage between phases and phases to earth for 1 minute. At voltages higher than 20 000, where on metal-clad gear the use of condenser-type bakelized paper is practised, the design should be made for the same standard of breakdown pressure, but, to reduce the risk of over-stressing, the pressure test might well be reduced by 10 per cent. For example, a good insulation on 33 000 volts is one that would break down by flash-over at not less than 120 000 volts, and puncture at not less than 180 000 volts. This should sustain no permanent injury when tested to 90 000 volts.

It must be borne in mind that the high-pressure test is not the only criterion. It is a measure of the initial strength but not necessarily a measure of its vitality. The latter must be judged by the result not only of the electrical but, in addition, the mechanical, microscopic and physical examination on "type tests."

Excess-pressure dischargers.—It is sometimes difficult to understand the need for the very expensive lightning arresters which are installed in other countries, as compared with the experience in this country. It is true that higher voltages are employed, but the insulation should be better able to withstand the excess-voltage conditions. It is probable that lightning has been made a scapegoat to explain away many failures which in reality have been due to inferior insulation at the start.

A high-frequency surge of excess voltage may be disposed of broadly under two methods: (1) to absorb it upon the line itself or (2) to allow it to discharge to earth. A direct lightning stroke must flash over the nearest insulators, but surges from atmospheric causes or by induction from lightning effects or switching operations are within the scope of protection. Where cables can be laid in series with the overhead lines, the result is achieved without any additional protective

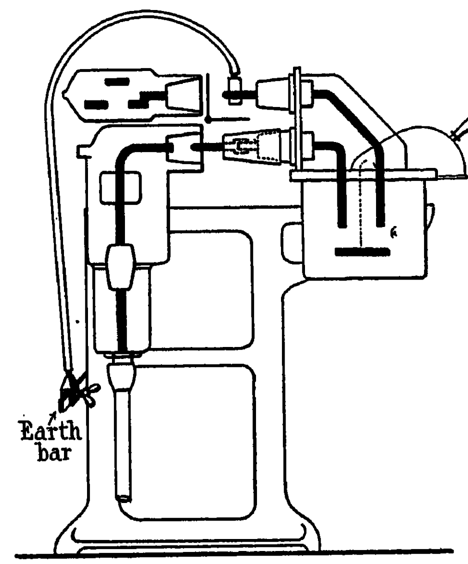


FIG. 24.

appliance. The excess voltage is absorbed in the capacity of the cable. This method, together with a high standard of insulation, satisfies the conditions prevailing in this country. The discharge method first involves the combination of gaps over which the discharge starts, and then devices to seal up the path and quench the discharge, or in some way prevent the following on of the power current. In one design on metal-clad lines the discharge is made over a number of narrow air-gaps formed between flat surfaces in a pile of copper discs, the flow of power current being limited by a resistance immersed in oil. The whole device is mounted in a metal-clad carriage which is plugged into the switchgear orifice (Fig. 23).

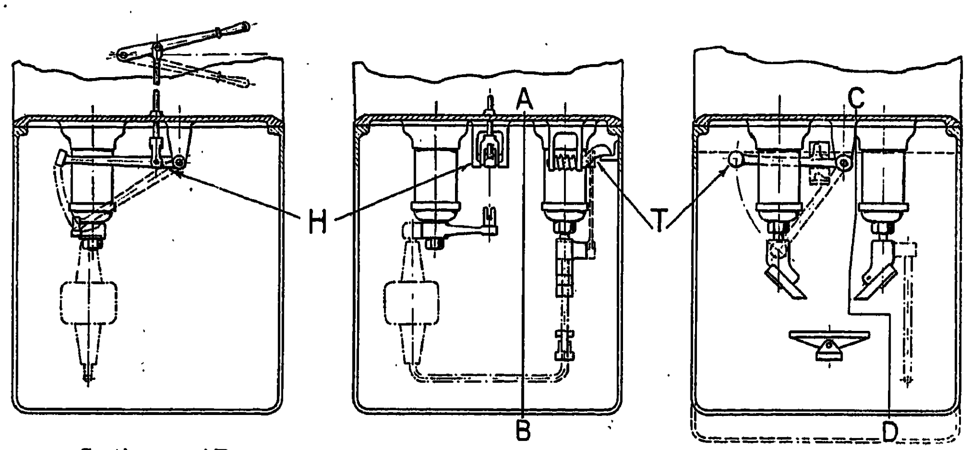
Safety to men working on the line.—The method of earthing at the end of a line on which men are going to work is indeed a matter of life and death not only to the men on the line but also to the operator who has to make the earthing connection. To him there is the risk of a conductor being "alive" by mischance. The wrong panel may be taken or a chance connection another way round forgotten. The flicking of a high-

tension conductor with a cable, in order to ascertain if it is dead, is on a par with pointing pistols or looking for a gas leakage with a naked light; and yet in many switchgears it is the only means available. Without exception the final closing of the earth connection should be done within an oil-filled enclosure, for example on the contact of a circuit breaker. Then if any mistake is made it will be no more serious than closing on a fault. Further, this may be limited to a single-phase fault to earth if a trial is made on one phase only at first. Fig. 24 shows an assembly of plug contacts, terminals, and earthing cable, which serves this object. In another design a hand-operated earthing contact is included as a component in the oil-immersed isolating switch; this is shown in Fig. 25. This figure also shows a convenient means of earthing automatically and simultaneously with the lowering of the switch tank.* This is vital when the lowering of a tank might otherwise expose a live conductor, or when there is any risk of the exposed conductor subsequently becoming dangerous to handle, for example, by electrostatic leakage across the oil between the contacts of an opened oil switch, by the inadvertent closing of another switch or by other mischance.

Indicating and interlocking.—Direct indication of "on," "off," "synchronizing," etc., placed on detail apparatus in a bold style, in a conspicuous position, and indication by coloured lamps serve a very useful purpose in the elimination of operating mistakes. A more complete method which has been adopted in several recent power stations is shown in Fig. 26, where discs give a semaphore type of indication on the control board. These discs are planned with the main connections like a single-line diagram, and are operated simultaneously with the switchgear components which they represent, by means of small electromagnets mounted on the back of the panel. The indicators are controlled by mechanical movements associated with interlocking devices to ensure a proper sequence of operation to avoid danger. The scope of this section is by no means limited to switchgear. For example, electric signalling and interlocking on railway tracks, if universally applied, might be the means of avoiding a wastage of life on a scale which must be very large compared with the number of mishaps on switchgear, for instance.

Economizing switchgear.—The cutting down of strength and qualities of designs and materials on important switchgear is doubtful economy. The cuts should be restricted to reducing the required number of functions, appliances, and constructional features. For example, an oil switch-fuse * combined with a transformer to form a small outdoor substation as shown in Fig. 27 takes the place of switchgear panels, transformer and connections in a building.

The single-switch substation scheme † reduces the number of switch panels required in the ring main (Fig. 28). At the same time it provides for the automatic isolation of a faulty section in the ring without discontinuing the supply to the other consumer. In this case the cable and power transformer are linked together in protection under the voltage-balance system by means of a "tee." The fuse arrangement acts also as a hand isolating-switch.



Section on AB. Section on CD. Section on AB.

FIG. 25.

H = hand-operated earthing contacts.
T = tank-operated automatic earthing contacts.

FAULT ISOLATION.

Discriminating protective systems.—The continuity of supply cannot be maintained during fault conditions unless devices are incorporated to pick out the faulty section or sections and to leave the sound sections undisturbed. In this country the problems of discriminating protection have had constant attention ever since the time when Leonard Andrews criticized the universal use of fuses. This development can be traced in the papers and discussions given in the Bibliography at the end of the paper.

Stability ratio.—The criterion of quality of any protective system is its stability ratio, i.e. the ratio between the maximum "straight through" current and the minimum fault-current setting that can be procured

* F. Coates and Mirrey.

* Gregory (Electrical Improvements, Ltd.).
† Beard (Electrical Improvements, Ltd.).

without any risk of inadvertent tripping after taking all the disturbing influences into consideration.

The growth of the fault current on the occurrence of a short-circuit is extremely rapid, and it is not possible to prevent it from reaching its maximum current value by making the protection sensitive. Even if it were practicable for the relay to have no electrical and mechanical inertia, there is still the comparatively long interval, say three or four periods, during which the circuit breaker is accomplishing its train of movements. It is therefore wrong to rely upon sensitiveness to limit the maximum current stress on the system.

What matters most is the acceleration of all moving parts right up to the separation of the contacts of the circuit breaker, the aim being to reduce to a minimum the period during which the fault is allowed to damage the system. It is not safe to depend upon limiting the amount of fault current by inserting resistance between the neutral point and earth. This can only help on the occurrence of a fault to earth, and no amount of scheming with protective gear will prevent the possibility of simultaneous earth faults occurring on different

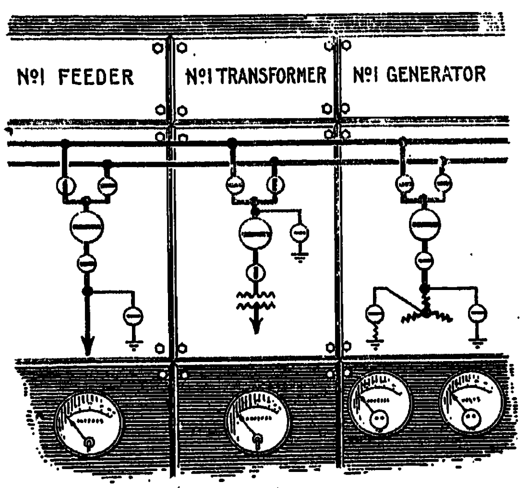


FIG. 26.

phases, maybe on different parts of the system. Every aspect, including relay settings, must therefore be subordinate to the maximum current possible on short-circuit between phases. In this light the value of the resistance connecting the neutral to earth is a matter for discussion. Certainly the stability of protective gear should not be sacrificed for the sake of ultra-sensitive relay settings, the need for which is solely due to the desire to cut down the amount of the earthing resistance. Rather save the entire cost of the earthing resistance and secure solidity by connecting the neutral direct to earth. For feeder protection this would permit the use of robust relays set like overload protection at 2–3 times full-load current, according to the size and position of the feeder. In the case of generator protection, in addition, the relation between the fault setting and the neutral earthing resistance also determines what proportion of the alternator winding is covered by the protection against single earth faults. The resistance may reduce, to a value below that at which the relay will function, the amount of current flowing into the fault in those parts of the winding nearest to the neutral point. If this were to happen, the fault would continue without disturbance until it developed into something more serious, or until it was observed

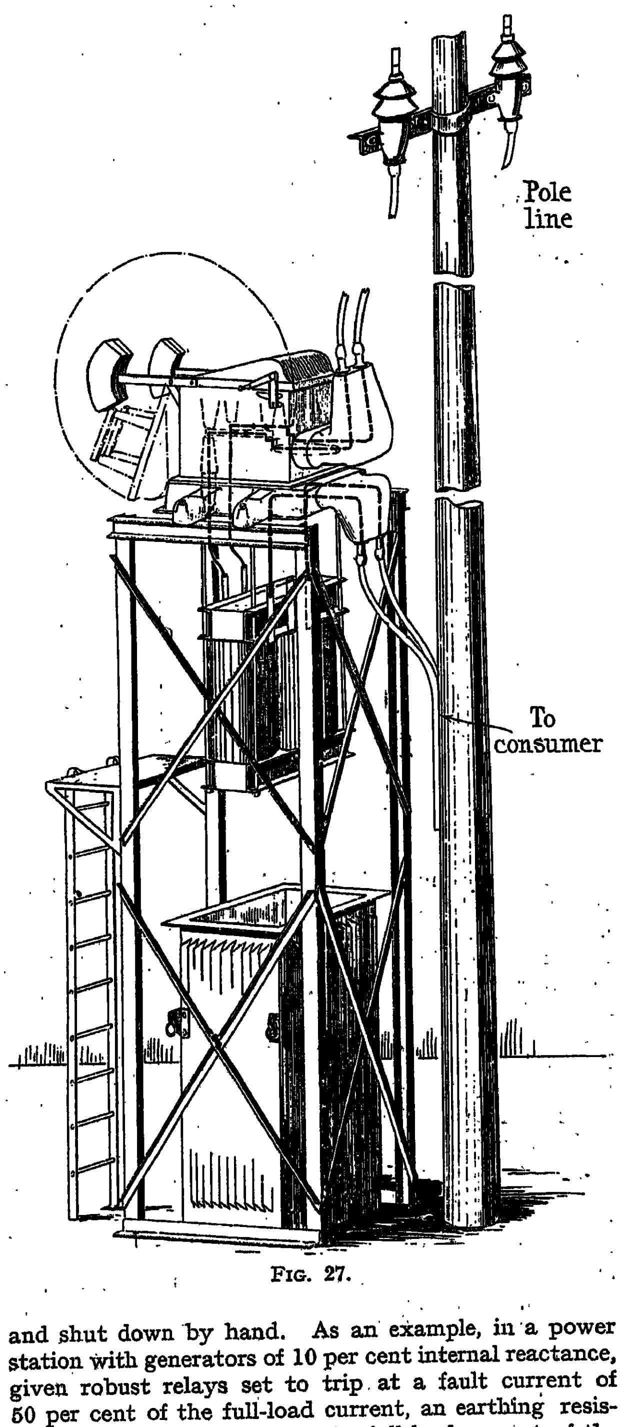


FIG. 27.

and shut down by hand. As an example, in a power station with generators of 10 per cent internal reactance, given robust relays set to trip at a fault current of 50 per cent of the full-load current, an earthing resistance which will allow twice the full-load current of the largest single generator to flow, and a stability ratio of not less than 40 : 1, there will be no inadvertent

tripping on any possible amount of "straight through" current. The whole of the stator winding will be covered for faults between phases, and 75 per cent of it for single earth faults. If more than this is required, either the relays must be made more sensitive or the ohmic resistance must be reduced. The former may be the more economical if the resistance must be retained, but the latter is better when considering comprehensively the protection of the whole supply system; and, if carried out to the full by the elimination of the resistance altogether, it would also be the most economical.

A robust relay such as is used in Merz-Price and split-conductor protection is one which has a simply constructed electromagnet to lift an armature, thus making contact and releasing a block contact which falls and serves the dual purpose of an additional circuit-closing contact and of an indication that the relay has operated. In practice a robust relay of this description may be set to trip at about 0·8 volt-ampere. A relay of this kind should not be subject to inadvertent tripping by any ordinary mechanical shock. Perhaps one of the best practical tests is to fix the relay to the base-plate of a turbine. If the vibration (which is the strongest form met with in a power station) does not trip it, it may be regarded as sufficiently immune from inadvertent mechanical tripping.

In contrast with the robust relay, sensitive relays have been used which can be set to trip at about 0·025 volt-ampere. This follows the line of a delicate instrument with a moving element rotating on pivots.*

Unbalancing influences.—Sensitive settings are jeopardized by several unbalancing influences. The capacity current in the pilot wire is one that is well known. Inaccuracies in the characteristics of transformers used in pairs "bucking" (one "bucking" against the other) may sometimes be due to careless assembly, but, in addition, phase-angle errors arise due to variation in the permeability of different batches of iron, and these errors cannot be entirely wiped out by mechanical skill and adjustment, however carefully the transformers are assembled.

Generally speaking, the current entering into a section is the same in phase and amplitude as that going out. This does not apply, however, in the case of oscillations in a cable carrying "straight through" current when the cable, acting as a condenser distributed throughout its length, is in series with heavy arcing. The cable, discharging over its whole length towards one end, passes more current at that end and sets up in the pilot-wire circuit an induced high-frequency transient which has proved to be sufficient to cause inadvertent tripping on long lines used for 33 000-volt and 66 000-volt transmission.

The influence on the pilot cable of direct induction between the cables themselves is unusual, but it has been encountered upon the same 66 000-volt system, so much so as to be the suspected cause of breakdown of the insulation of the pilot cable. This occurred on a single-cable three-phase system. Fortunately there are remedies for all of the unbalancing influences so far encountered, and these will be referred to in the following brief account of some of the forms of protection now in vogue.

Two-core pilot.—This system of Merz-Price protection has been devised as a means of reducing costs, and has been obtained by combining two of the earliest systems:

(*a*) The voltage balance, with transformers on two phases and 2-core pilot * (Fig. 29).
(*b*) The core balance leakage † (Fig. 30).

These combined give a system (Fig. 31) which is simple and is suitable for use with instantaneous relays of a robust character. For example, it may be used on ordinary feeder lines 2 miles long where the "straight through" current on short-circuit might be 10 000 amperes. The relay settings would be about 400 amperes for "between phase" faults and earth faults. Thus the stability ratio is 25 : 1. For longer lines the pilot capacity-current becomes effective and higher settings of the relays would be required in order to retain stability.

Balancing condensers.—To compensate for the unbalancing influence of the capacity current one of the earliest suggestions was the use of condensers.‡ This method has been experimentally applied, but in practice

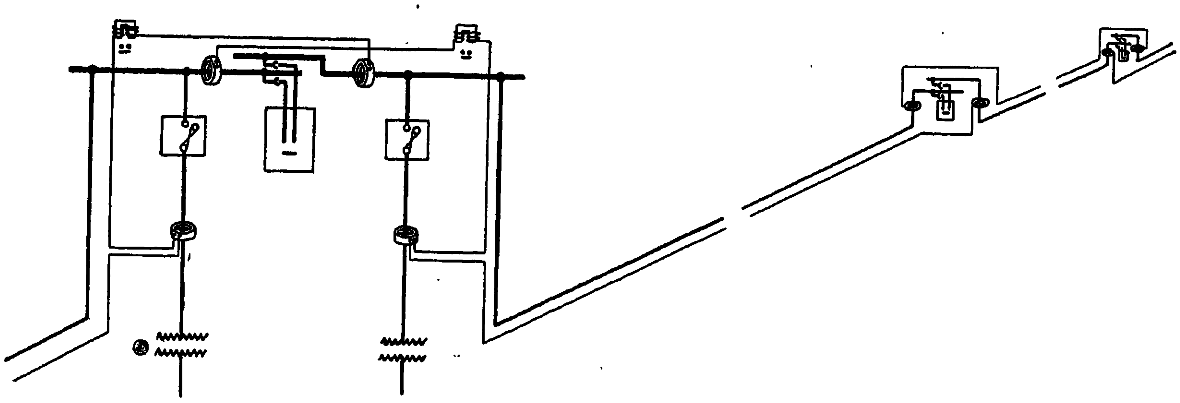


FIG. 28.

* Fawssett-Parry.

* 1904 Patent. † 1908 Patent. ‡ Whitcher.

in this country the compensated pilot found greater favour.*

Series relays.—As an alternative when the further stabilizing element is necessary, and when compensated pilot cables may not be used on account of additional expense, an arrangement with two relays in series has some points of interest.† One relay has a slight lag due to added inertia, but a sensitive setting; the other has a comparatively heavy setting but instantaneous action. The inertia relay deals with small and ordinary internal faults with a slight inverse time-limit, but is unmoved by the out-of-balance set up by heavy "straight through" currents. The instantaneous relay deals with the heavy internal fault currents that are of importance from the aspect of speedy release.

Diverter relay.‡—The above principle is carried a step further by the diverter relay system devised at an earlier date. This is illustrated in Fig. 32. In this case the relative action of the inertia relay and of the instantaneous relay respectively is similar except that the instantaneous relay does not trip the circuit breaker directly, but only makes the inertia relay more stable against the unbalancing influences by adding resistance

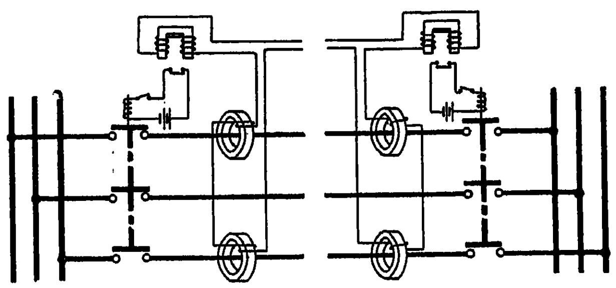


FIG. 29.

in circuit with the coil whilst the heavy "through" transient is passing. As compared with the preceding example, with a corresponding length of line the earth-fault setting may be reduced from 400 to 100, and the stability ratio increased from 25 : 1 to 100 : 1, notwithstanding the influence of the pilot capacity-current. By reducing the effect of this capacity current, which can be done by a simple modification as shown in Fig. 32A, the length of line may be increased to 10 miles with the same stability ratio.

Applied to feeder protection of long lines where unbalancing by oscillating currents is to be feared, the inertia relay coil may be by-passed by a non-inductive shunt resistance which will prevent the bulk of the high-frequency current from traversing the relay coil. This is really additional stability. Without the "by-pass" the inertia would be sufficient to tide over the short time during which it is possible for the transient to exist, assuming, of course, that the "through" fault will be properly cleared by its own relays.

Tuned relays.—A more positive method of elimination of the unbalancing influence of the oscillatory currents is a relay which can operate only with a flow of power current of or about the normal frequency of the system. A proposal * utilizing contacts mounted on reeds mechanically tuned to correspond to the natural frequency has shown promising results in its experimental stages.

Drainage coils.—The remedy for the vagabond induced voltage on the pilot wire is similar to that which has been applied to telephone circuits. Differentially-wound induction coils are connected to each phase of the pilot wire. These form a non-inductive path to earth for the induced current, but a highly inductive path for the normal currents which circulate in the pilot wire at the instant of a fault. These "drainage coils" have been tried and do not materially interfere with the fault tripping-values of the relays. The risks can be reduced to a minimum by good bonding at the joints in order to avoid the earth-return fault current taking a vagabond path. If it returns via the lead and bonding the resultant field of the outgoing and earth-return currents will be neutralized.

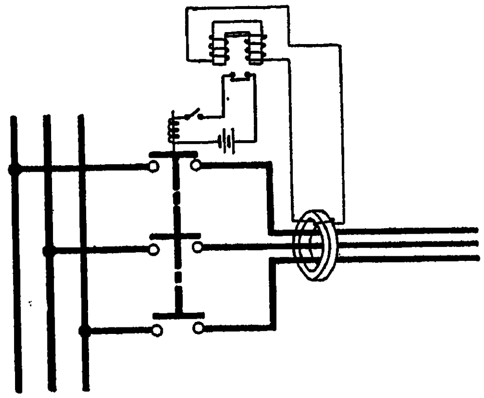


FIG. 30.

Extreme measures.—As a record, an aggregation of the foregoing on a 3-core pilot system is shown in Fig. 33. One side of the diagram shows the use of compensating condensers, and the other the compensation by pilot-wire sheath. Fortunately, the use of all the accessories is necessary only on very rare occasions.

Time-limit discrimination.—Relays with a definite time-limit action by pendulum or clock mechanism have still a place as positive discriminating devices for graded feeder and plant sections in series, whether in single line, tree or tee formation. Their scope is, however, restricted in those places where continuity of supply is all-important, and where in contrast the fundamental demand is for instantaneous action and parallel running, which includes the case of ring mains. The same limitation holds for excess-current time-limit relays with inverse time characteristics and with or without minimum definite time-settings.

Split-conductor system.—The split-conductor protection is exceptionally useful as a system involving practically no expense when two existing cables † can be used in parallel on one split-conductor switch. In fact, sometimes the entire cost of two switchgear panels can be saved (see Fig. 34).

Four-core protection.—A combination of Merz-Price

* Beard-Hunter (Electrical Improvements, Ltd.).
† Beard-Porter (Electrical Improvements, Ltd.).
‡ Biles.

* Leeson. † Glasgow and Sheffield Corporations.

gear with the split-conductor system, known as the 4-core system,* is said to be the most economical in new cables from a cable-making standpoint (see Fig. 35).

Generator and transformer protection.—The stability of Merz-Price generator and transformer protection is also dependent upon the accurate magnetic balance of the current transformers and, as for feeder protection, in some cases there is the need for rendering it more secure by adding to the plain relay, pilot and transformer system some stabilizing feature such as the "bias" * or the "diverter" relay. With the latter the fault-setting may be reduced to 10 per cent, the stability ratio increased to 200 : 1, and, with the resistance to pass twice full load, 95 per cent of the winding will be protected, or, with the resistance reduced to full load, 90 per cent of the winding will be protected.

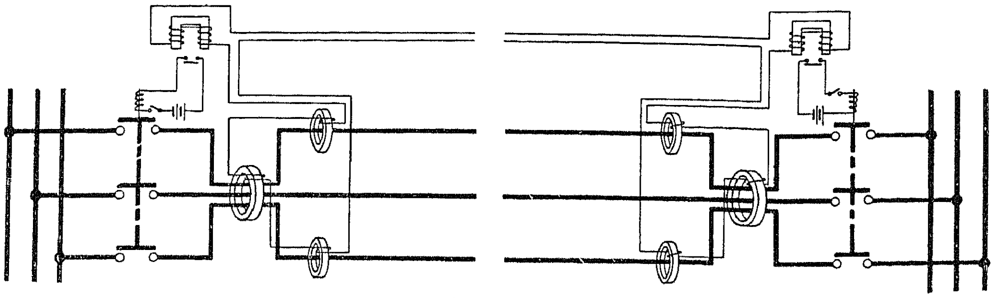
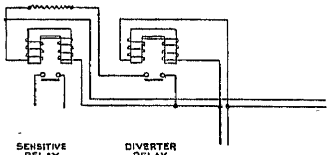


FIG. 31.

FIG. 32A



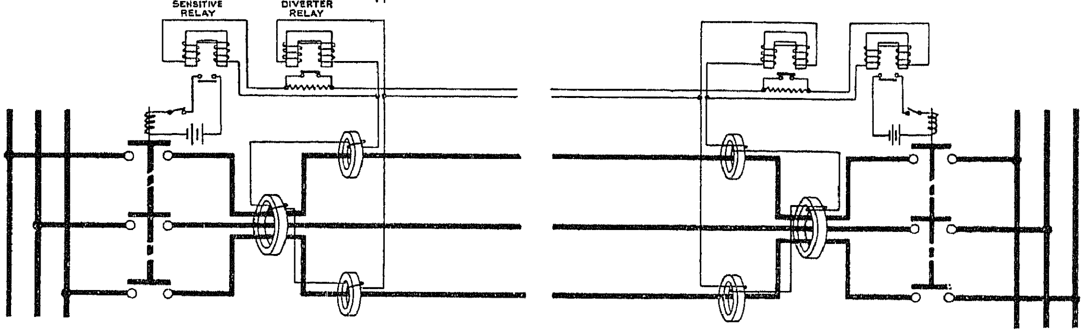


FIG. 32.

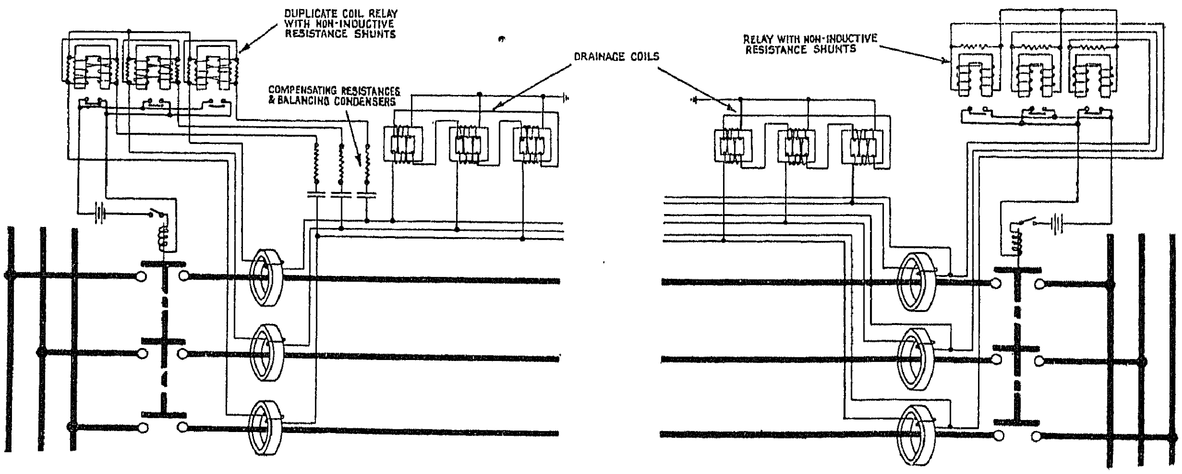


FIG. 33.

* Hunter.

* Wedmore and McColl.

Generator field and auxiliary circuits.—The study of generator protection has included the possibility of a failing field. The best remedy is a thoroughly reliable air-break main field switch which will not inadvertently trip out, and efficient insulation, which latter is not difficult for the low voltages employed. The excitation of modern alternators is provided by their own exciter unit. Overload cut-outs are undesirable and unnecessary. Both poles are insulated so that a fault to earth, such as an accidental contact with a spanner on one pole, does no harm, and even this can be avoided by proper enclosure. Reverse-current relays controlled from the a.c. side are frequently inoperative on a failing field and their application is limited to a failure of the prime mover. Although recent designs are greatly improved, such relays cannot be considered desirable for alternator protection. In any case it is essential that they be fitted with a definite time-lag to prevent premature operation. In these circumstances it would appear to be unnecessary to introduce any failing-field tripping device, but if one is installed it should have a long, definite time-limit attachment. Here instantaneous action has no great significance from the point of view of limiting damage or disturbance to the continuity of supply. In fact, the rare occurrence of a failing field may safely be left to manual operation.

The further steps of closing the ventilating shaft and steam stop-valves are all to the good in limiting the possibility of the fire spreading inside a machine, but the automatic cutting-out of a fault should be effected so rapidly that a serious fire cannot start.

Generator auxiliaries are an important factor in the continuity of supply. The inadvertent closing down of auxiliary plant is frequently responsible for discontinuity. Infallibility of switchgear and connections will do much to prevent this annoying experience. For this reason it is important that the mechanism involved on the many circuits shall be very solid, notwithstanding that some of these circuits may be quite small and apparently insignificant. In large power stations the power behind the switch is considerable, and the ordinary service fuse equipment and low-tension switchboards are generally inadequate. There should be nothing in the nature of low-voltage releases, or anything that may be accidentally tripped out in cleaning operations. Fuse protection, provided the fuses are heavy enough to prevent premature blowing on occasional overloads, is permissible, but, as complete enclosure is essential, special measures are necessary to contain the forces of the explosion created by the blowing of a fuse on the occurrence of a short-circuit. Low-tension, metal-clad, oil-immersed fuses have been made for this purpose.

The other part of the problem of continuity concerns the layout of an alternative source of supply to the

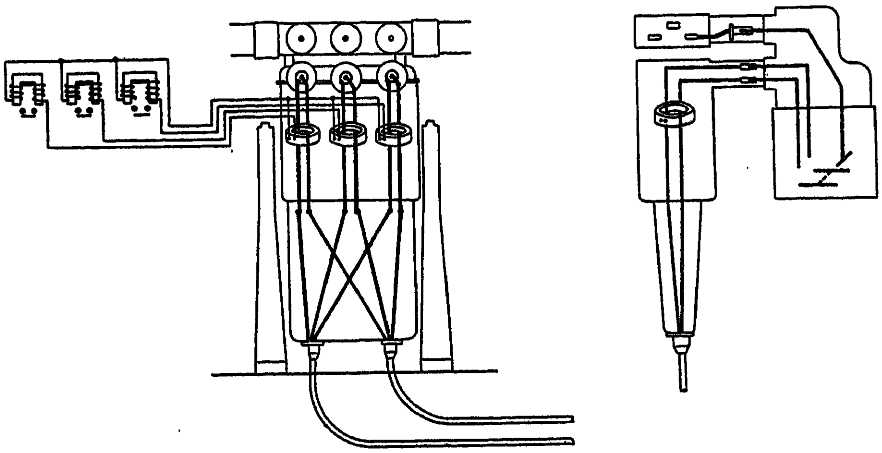


FIG. 34.

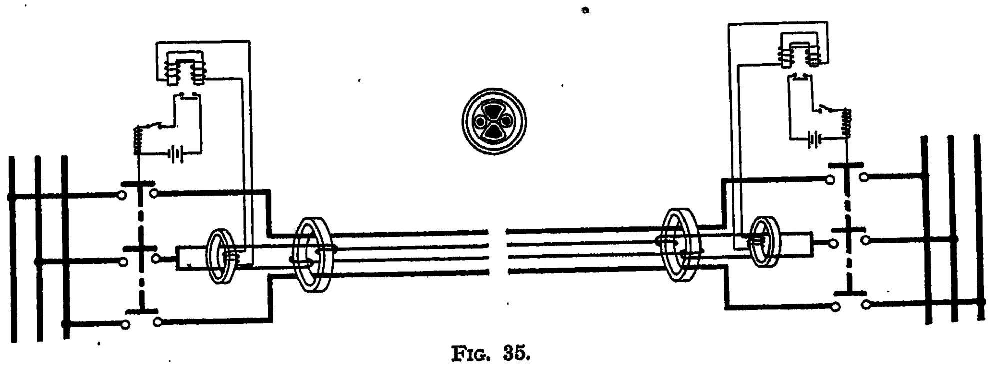


FIG. 35.

motors controlling the auxiliaries. One source may be a separate transformer attached electrically to the generator terminals on the unit system—i.e. it comes under control from the busbars through the same main circuit breaker as the generator—and the other a transformer supplied from the station busbars.

The plant must start up from the busbar transformer, and when the generator is running it may be changed over to the generator's unit transformer. The point of change-over from one system to another is a delicate and yet essential one. There is often a risk of the significance of this important detail being overlooked, as, for instance, in the transference of the requirements of a specification from one department to another. The importance of this equipment merits the best in design, and absolutely positive action; there must be no possibility of failure of operation. One switch must first break the whole auxiliary load, its contact being well clear, and simultaneously with that clearance the other switch contacts must close. The two switches must never make contact at the same moment, because the busbar transformer may at some time or other be taken off a section of busbar which is not in phase with the unit transformer.

Similar switchgear arrangements are suitable in those cases where the alternative supply to auxiliary plant is given by steam-driven house turbo-alternators. The layouts may differ in detail, but the principle represents the requirements for present-day practice.

Self-balance.—The phase-angle errors and unbalancing influences to which any two transformers in the same protective circuit are prone are eliminated by the use of a single iron core as in the system known as "self-balancing." * This core can be designed to slip over the lead of the main alternator cables and, in co-ordination with the design of the alternator frame, affords a good solution of the terminal question. Instead of bringing the terminals out underneath and out of sight as in the present practice, they might be given the prominence they deserve by being brought to the surface (see Fig. 36).

At the side of the protective transformer and terminal box is shown the usual emergency pillar containing the main field circuit breaker and a press-button release for the main oil circuit breaker and the field switch.

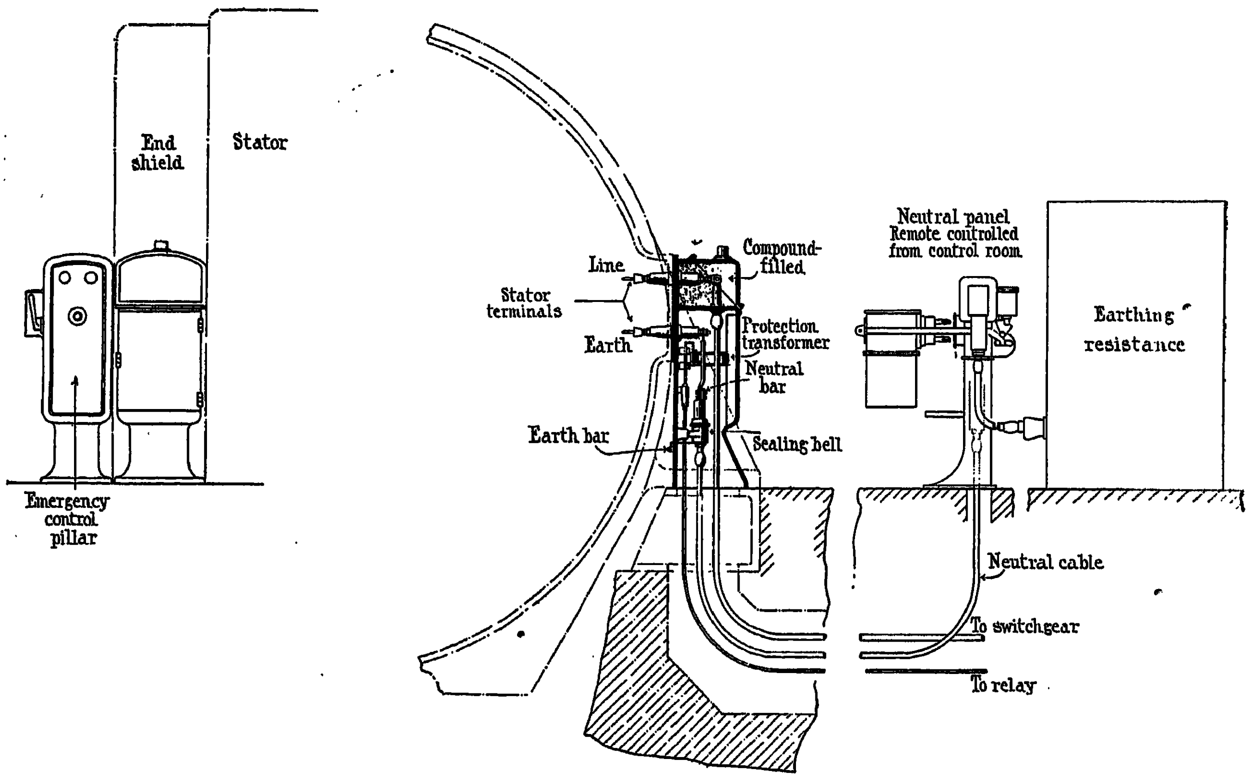


FIG. 36.

The diagrammatic scheme of connections, including protection, field control and interlock, is shown in Fig. 37.

The protection covers the stator windings, terminals, and the main cables to the switchgear. The relay contacts are arranged to open first the main stator circuit and, when that is accomplished, then the field and the neutral earthing circuits. The field may be closed by hand, but cannot be opened by hand while the stator is closed. The stator cannot be closed on an open field. An alternative is to allow the neutral earthing switch to open simultaneously with the main oil switch. The connections as shown in the diagram provide for this method.

Relay-tripping by hand for trial of mechanism from the control room opens the stator but not the field

* Beard (Electrical Improvements, Ltd.).

circuit. The emergency release on the engine-room pillar opens the main circuit and field circuit in sequence. The complete metal enclosure of all circuits, including the neutral, will be noted.

Interference with telephone lines.—The aid of protection against faults is evoked by the telephone and telegraph service in order to eliminate interference by currents induced from the main line during faults.* Currents at normal frequency of the line do not interfere so seriously with speech on telephones as those of abnormal frequency which may occur on transmission lines during arcing earth-faults.

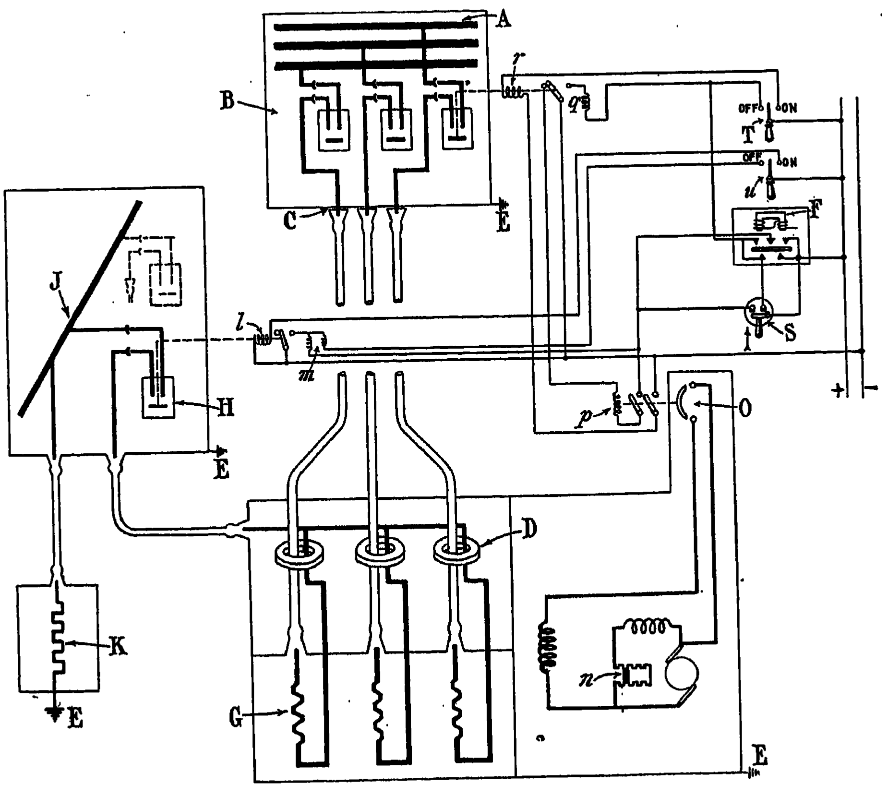


FIG. 37.

A. Main busbars.
B. Main oil circuit breakers.
C. Alternator cable gland insulated from earthed switchgear frame.
D. Self-balance current transformers (secondaries connected to winding of relay F) for self-balance protection against cable fault.
F. Relay. Armature operated upwards by self-balance protection and downwards by hand release for routine testing. The latter does not trip the field switch.
G. Alternator stator winding.
H. Solenoid control oil-break circuit breaker for neutral.
J. Neutral busbar common to all generators.
K. Earthing resistance.
l. Closing solenoid.
m. Trip-coils for hand and automatic control respectively.
n. Exciter shunt-field regulator.
O. Alternator field circuit breaker.
p. Trip-coil operated from relay F and emergency switch S.
q. Main circuit breaker trip-coil.
r. Contactor coil controlling the closing of the main oil circuit breaker.
S. Emergency control contactor located near alternator for opening main oil circuit breaker, followed at once by the main field circuit breaker and neutral earthing circuit breaker.
T. Remote-control switch for main oil circuit breaker.
u. Remote-control switch for neutral earthing circuit breaker.

The risk of shocks and fires from telephone and telegraph leads, occasioned by induced voltage, is one which must not be overlooked. In some places it has been found necessary to insulate telephone communication wires between substations as for high-tension service (3 000 volts), and to resort to the use of "drainage coils" of the type mentioned above in connection with pilot wires for protective gear.

The intensity of this form of interference depends upon the path taken by the return current from a fault. If the system can be arranged for the fault current to go and return along parallel paths in close proximity, the field of the outgoing conductor is neutralized by that of the return, and no currents would be induced in neighbouring cables. This requisite can best be obtained by completely enclosing all conductors in metal. This method, while providing an efficient bonding over all sections of the metal enclosure, reduces stray currents. Moreover, given an earthed neutral point, it tends to reduce to a minimum the possible duration of the high-resistance fault currents which set up the high-frequency oscillations. The duration of disturbances to speech can thereby be cut down to the short time taken by the protective gear to isolate the faults. Such interference would be unnoticeable to ordinary users of the telephone service.

To conclude, the variety of designs and possible causes of trouble on protective gear may create an impression of reluctance to depart from the simple overload devices, but it must not be overlooked that these overload devices are the greater offenders in inadvertent operation, and that the difficulties which

* S. C. BARTHOLOMEW: "Power Circuit Interference with Telegraphs and Telephones," *Journal I.E.E.*, 1924, vol. 62, p. 334.

have been faced are mainly those which have arisen out of ever-changing conditions of service, increased currents and voltages, and extension of the distances of transmission. There are innumerable instances of the simplest forms of balanced protection having given efficient operation ever since they were installed, some of them on a large supply system in 1906. Moreover, enormous benefit has been derived from them in the development of the large supply systems under the policy of universal interlinking and parallel running, with the consequent continuity of supply to all consumers.

Conclusions.

The requisites for safety and continuity are briefly as follows :—

(1) Universal metal-clad enclosure for :—

(*a*) The confinement of dangerous conductors;
(*b*) The preservation of insulation in compound and oil;
(*c*) The restraint of fire and arcs within a unit, and the impregnability of adjacent units; and
(*d*) The reduction of cleaning functions and other interference with conductors and insulators.

(2) A stable neutral point at earth potential, giving :—

(*a*) Durability of earthing and bonding;
(*b*) Stability on transient short-circuit "straight through" currents in sound sections, and instantaneous isolation of the faulty sections.

(3) Reliability in all operating mechanism, enhanced by periodical inspection and trial by hand-release of essential tripping movements.

(4) (*a*) Elimination of human error by security of interlocking, coupled with the indication of essential circuit connections.
(*b*) Strong flameproof enclosure for circuit-breaking elements.
(*c*) Reduction of destructive forces, if possible, but in any case the limitation of their duration to a minimum by all available measures.

The author begs to acknowledge that the paper is in the main the outcome of a long and close association in design and experience with the Operation, Testing and Construction Departments and the Consulting Engineers of the Newcastle-upon-Tyne Electric Supply Co., Ltd., and their allied Companies of the North-East Coast. In addition, he desires to acknowledge a large amount of assistance from members of the staff of Messrs. A. Reyrolle and Co., Ltd.

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Discussion before the Institution, 22 January, 1925.

Mr. E. B. Wedmore: Many phases of the work which are indicated in the summary of the paper are now largely common practice. The adoption of the principles underlying the metal-clad construction is in a large measure due to the author's personal effort. I am not able, however, to agree with the author on every point. In certain respects he is carrying his ideas too far. I refer particularly to the omission of duplication in certain cases. He is not in favour of the duplication of switches. Although the electric supply industry is very well served by expert purchasers and maintenance engineers, the repair bill of the industry runs into millions of pounds per annum. Insulation failures alone account for half a million pounds a year. No manufacturer intentionally offers defective apparatus, but these figures show that there are still weaknesses to be overcome, and that we have not reached finality in design. We have switch failures to record every year. I think there are instances in which maintenance of supply and other considerations

do tend to the duplication of switches. One cannot afford in a station where the supply rests principally on two or three large generating units, to face the position, even for a comparatively short time, of two of those machines being out of action. It means that when one machine is shut down we are absolutely dependent upon individual switches to keep the second and third machines running. The provision of duplicate switches in such cases sometimes carries with it other advantages, e.g. simplicity of the whole scheme and its operation. Where the supply to a large substation depends upon a few large power transformers, the question again arises whether one could not duplicate switches to advantage where a duplicate busbar system is employed. The author favours the use of a single busbar in large generating stations, but I altogether disagree with him. The use of simplified gear in a small compass is part of the practice advocated, but if a breakdown occurs, the result will almost inevitably be very serious and prolonged. The use of single busbars has been discussed before and I have sought for some analogy to illuminate the issue. It is to be found in the anatomy of the animal creation, in designs which have been evolved through countless ages and withstood the test of time. We find the rule is that the external exposed organs are duplicated and the single organs are the protected, the partially enclosed and the totally enclosed. So far the argument is with the author, but closer examination shows important exceptions. We find the brain or principal nervous centre amongst the best protected but always completely duplicated, each half with its independent blood supply, and to make assurance doubly sure we have at the base of the brain the best protected spot of all, the circle of Willis, which is comparable with the ring busbar, one of the ideal forms of duplicating, so arranged that any section may be damaged without stopping the blood supply to either half of the brain from either main artery. The single busbar in the large generating station has been tried experimentally in this country and found wanting. I have followed with great interest what the author has to say on the subject of rupturing capacity of oil circuit breakers, a subject upon which a great deal will be said in the next few years. The Electrical Research Association is happily in the position of being able, with the co-operation of power station engineers, to carry out on the rupturing capacity of switches researches which are revolutionizing design. The extraordinary range of action that is given when one and the same switch is called upon to open one and the same circuit under identical external circuit conditions cannot be too clearly recognized by all buyers and users of switches. A given switch may open a circuit with hardly any indication that anything has happened, but on the next test the same switch may be blown to pieces. The amount of energy released on one and the same switch on one test may be very many times that released in the next test under similar external conditions. It has been said in the past that half a dozen tests should be made on a switch before any idea can be obtained of its safe rupturing-capacity rating, but I now doubt if that number is sufficient with present designs. I am, however, happy to say that we are in sight of formulæ which will enable us to establish on scientific principles the true rupturing capacity of an oil circuit breaker. Until that is done it is of very little use to split hairs on small margins on supposed factors of safety based on data now current. Diagrams of protective gear are puzzles which mean nothing at all to those who are not familiar with the details, and I shall not pursue the details now, but certain interesting facts emerge when the designs recently developed in protective switchgear are examined. The modern motor-car or flying machine could not have been built 20 years ago, because we had not the special materials and special machinery which are now available for their production. There is no reason, however, why the most highly developed protective gear of the present day should not have been manufactured 20 years ago. I put that point to a designer to-day, and his reply was to the effect that at that time the necessity and the economic value and importance of protective gear were not realized. We have got past that stage and there is now a recognized market for effective protective switchgear. Of the various designs produced, each one has been the "last word." This suggests that finality has not yet been reached, and anyone who will make himself familiar with the requirements as detailed in the papers cited in the author's bibliography, and will apply himself to the outstanding problems, may expect to make further advance. When the Hunter four-core system was evolved, I spent some weeks trying to improve on it with a single pilot in the middle of a cable. There are many ways in which it cannot be done, but it should be possible. At any rate, the next step will be something on those lines, and I suggest that those who are interested in the subject should pursue the idea.

Dr. C. C. Garrard: I should like to suggest that while the author's methods are no doubt excellent when the conditions are suitable, he goes too far when he maintains that they are the only methods. The author's clear exposition of the term "stability ratio" expresses in two words what would otherwise take a great deal of explanation. It is an all-important matter in protective gear. Applying it to a given case, if the short-circuit current be, say, 50 times the full load of the circuit, then the minimum fault setting one could have, given a stability ratio of 100, would be 50 per cent of full load. I would recommend that the B.E.S.A. Committee on Nomenclature should consider the standardization of this definition. Reading between the lines of the paper, it would appear to me that the author's scheme for dealing with a low stability ratio is to increase the fault setting. To my mind the proper solution of the stability problem is the adoption of the biasing principle. This can be done in a variety of ways. For example, mechanically or electrically in the relays, as in McColl's system, or by the use of a biasing transformer, as employed by FitzGerald. The diverter relay in Fig. 32 would be a form of biasing were it not for the fact that it puts in the bias in one step, the fault setting being altered suddenly at one particular value of the load by the

insertion of the resistance. The biasing principle in the systems I have mentioned is, however, effective over the whole range, its effect being to make the fault setting a constant percentage of the load flowing at the time. Thus the stability ratio is enormously increased. There can be no doubt that in the future this bias principle will be more and more applied. It can, of course, be used in conjunction with any system of pilot-wire or split-conductor protection. It might be thought from the heading of the paragraph on page 442 that the bias system can only be applied to generator and transformer protection. This is, of course, not so; it is of universal application. In passing I would add that the use of an "inertia" relay seems to be contrary to the spirit of the author's remarks elsewhere in favour of the instantaneous action of protective gear. I quite agree with his preference for the term "mistake-proof." What we have to guard against is an attendant operating without thinking. As long as his attention is drawn by some means to what he is doing, for example, by finding it impossible to open a link door without having first to open the oil-switch chamber door, this is generally, at least in power station work, as far as it is desirable to go. Complicated interlocks on power station boards, operated by skilled attendants, are in my view very undesirable. They can introduce a false assumption of security. I know of a case where a highly-skilled engineer was killed because he relied upon an interlock, and another case of the representative of a firm which specialized in interlocks having his arm burnt off in spite of all these precautions. Simplicity, ease of inspection and flexibility are vital in power station switchgear. It is certainly good practice to inspect periodically all connections and joints on important installations, and in my view it is desirable that this should be made possible. For large power houses I believe the fireproof subdivided system, developed from the original cellular gear of Ferranti, gives the most satisfactory all-round result. This certainly seems to be the trend of events in America, where the largest stations (such as Hell Gate) are now installing the isolated-phase system in which the three phases are in separate and distinct rooms. The advocates of the totally-enclosed compound-filled type claim, with justice, that this scheme is free from the danger of busbars being short-circuited by rats or mice. This is true. But cellular gear, as now constructed, is vermin-proof, and mica-insulated busbars and connections are an additional safeguard. In making these comments I wish to point out that I do not for one moment make any exclusive claims for the cellular construction. The totally enclosed scheme has many legitimate applications; I merely deny that it is the only right system. As regards the form of reactance mentioned on page 427, I should like to ask the author if he can give any figures as to the internal losses in the lead-covered cable type, as compared with the bare-wire type. I am inclined to think that they are rather large. On page 428 the author seems to deprecate the use of duplicate busbars in large power stations. I should hardly think he is serious in this, and I cannot conceive it possible that any large power station will be built without duplicate busbars. I think that the remarks in the paper regarding B.S.S. No. 116—1923 require some discussion. The general drift of the paper in this matter would seem to be that this specification rather leans towards a low standard. This is, however, to misunderstand the specification. In the appendixes of the specification, suggestions are given as regards the selection of oil circuit breakers. These are attacked by the author, and I think that his Fig. 19 is calculated to do a certain amount of harm to British reputation. The B.E.S.A. specification leaves it open to the purchaser to specify the factor of safety he requires. In order, however, to guide him in the rather complicated matter, the suggestions in the appendixes are given. It may be added that these suggestions have a large amount of practical experience behind them, and are to all intents and purposes the same as those adopted by the American Institute of Electrical Engineers. The real crux of this question is the rating as regards rupturing capacity given by the various makers to their switches. Generally this is in inverse ratio to the reputation of the maker. If the purchaser were sure that the maker's rating was a true one, he would not go very far wrong if he followed the specification. There is of course a great deal yet to be known about the question of breaking capacity. The author touches upon one, viz. the effect of reactance (page 434). It may be necessary in the future when specifying breaking capacity, to specify the power factor, but we are hardly in that position yet. The expression "through rating" of a circuit breaker used on page 434 seems to me to be the same as its rupturing capacity rating, and I should be glad to know whether this is so. I agree with the author's remarks in regard to "explosion pots" in oil switches, and I would also point out that with switches on 5 000-volt or 6 000-volt circuits it is necessary for the "pot" to embrace only the arcing contacts, not the main contacts. In my opinion it is the secondary explosions (in the air space above the oil) which have been the cause of most of the disasters with oil-break switches in the past. I doubt whether the explosion-pot construction helps in such cases. As regards the use of charging resistances in oil switches, these are very advantageous in transformer switches. There is generally a large rush of magnetizing current when switching-in a transformer; with a plain oil switch this not only affects the protective gear but is bad for the apparatus generally. It can be entirely obviated by a self-contained charging resistance mounted on the moving cross-bar of the switch. I disagree with the statement on page 438 that "without exception the final closing of the earth connection should be done within an oil-filled enclosure." When my own safety is in question I prefer an earth link which I can see is closed and in perfect contact with its jaw: personally I should never rely upon something I cannot see. I also must protest against the author's vibration test on the base-plate of the turbine (page 440). I think that the crane often affects the switchboard more than the turbine does. The necessity for the use of drainage coils, compensating condensers and the like, mentioned on page 441, shows

how complicated protective gear can become. I should like to know to what extent these are necessitated by the necessarily relatively high voltage on the pilot wires when using the balanced-voltage system. It seems to me that the circulating-current system for cable protection is free from many of these difficulties. I think that the author's remarks (p. 435) on the question of reactance coils must be accepted with caution. Reactance coils are an absolute necessity in large stations. They should, in my view, be installed so as definitely to limit the short-circuit current to a maximum value not exceeding, say, $\frac{3}{4}$ million kVA. This provides no difficulty even with the biggest possible plant.

Mr. T. C. Christianson: I gather that many operating engineers dislike interlocks for various reasons. There is a limit in practice to the amount of interlocking which can be applied to switchgear and other apparatus, and with very complete interlocking there are occasionally circumstances requiring some of the interlocks to be temporarily put out of action—in such circumstances special care is essential to avoid accidents. I think most engineers will agree that complete enclosure or inaccessibility of all live connections with plant of large capacity is highly desirable, and it should be noted that low-tension apparatus should be treated as carefully in this respect as high-tension apparatus. I know of at least one fatality resulting from arc burns following a short-circuit set up by the metal on a portable instrument on a 440-volt switchboard. Many engineers prefer, however, that the enclosure of switchgear and its accessories should be of the cubicle rather than the complete metal type. Cubicle-type switchgear has several merits which one feels will always appeal to many engineers. On page 430 the author mentions an entire switchgear being destroyed due to a fault, and the inference appears to be that this switchgear was of the cubicle type. I think it only fair to say that faults on metal-clad gear have occurred, and that while their effects have generally been concentrated, repairs and resumption of supply have taken a good deal of time. It must be recognized that the effects of faults when they do occur on the cubicle type of gear are in general more readily rectified than those on metal-clad gear. A change-over on duplicate busbar cubicle-type switchgear is quite simply and easily arranged for. The majority of engineers will agree with the author that one good circuit breaker, etc., is better than two of inferior quality, and that with metal-clad switchgear the necessity for a duplicate busbar for cleaning purposes scarcely arises. Even with the best design of apparatus, however, faults are possible; therefore one would naturally prefer to have duplicate busbars at vital points on the system, such as the main generating station, to permit—among other reasons—the supply to be resumed quickly from the hospital busbar after a fault on the main busbar. A further advantage of duplicate busbars at, say, the main generating station is to permit the practice of normally running some of the generators and feeders on one busbar, and other generators and feeders on the other busbar—separated when the capacity of running generators is large except through reactors *per se*, or through network feeders with their inherent impedance. I think that the author will agree that under both the above heads it would be a distinct advantage from an operating point of view to be able to effect the change-over from one busbar to the other in the shortest possible time. It is a fact that faults on metal-clad busbars have been of rare occurrence, but it is probably worth while to arrange (and pay) for the means to enable a rapid change-over to be made when such a fault may occur. Again, under the second heading mentioned above, some engineers are probably prepared to pay for the means of enabling circuits to be changed over—for adjustment of load, etc.—without interruption thereto. I think that the author has mentioned that in most cases feeders, etc., would be at least in duplicate—so permitting a short interruption of power supply through one feeder without interfering with the supply of power to any given location. It will be appreciated that simple but efficient interlocks can readily be applied to most of the change-over devices mentioned by the author in order (*a*) to prevent both busbars being connected simultaneously to any circuit under any conditions; (*b*) to prevent both busbars being connected simultaneously to any circuit except when the two busbars are paralleled through, say, a busbar coupler switch; and (*c*) to necessitate the circuit breaker being open before any operation can be performed on the isolating switches. I believe that some operating engineers would prefer to change over without interruption with or without interlocks, and that others would prefer definitely to interrupt the supply to each given circuit—even if only momentarily—for change-over purposes. It would appear to be mainly a question for operating engineers to determine their requirements in this regard, and we manufacturers hope that they will give us their views on the necessity or desirability of these various features, bearing in mind that what we may call the rapid change-over features are somewhat more costly than the others. Referring to Fig. 9, a further point in regard to the design shown therein is the simple means available for earthing either of the busbars or the cable by inserting earthed plugs in the appropriate sockets and closing the oil circuit breaker. It should be noted that the design—under Patent No. 217290—covers bottom sockets with through insulators for bottom plugs to connect the circuit breaker terminal to the cable or earth as required, as well as the two top sockets indicated in the figure. There is the further feature not discernible from the figure, viz. that the oil circuit breaker may be of the normally fixed type. Referring to Fig. 8, I consider it to be of prime importance with this design of change-over arrangements that (*a*) positive means should be provided to prevent both busbars being connected through plugs associated with any one circuit oil circuit breaker other than the busbar coupler, and (*b*) that a positive indication should be given as to which busbar is connected to the oil circuit breaker. The indicator should, therefore, be automatic and should not depend merely on the operator's memory at the time of change-over. The double oil circuit-

breaker layout would appear to be the best for duplicate busbar working, and its greater cost is probably justifiable in large and important stations. I think, however, that engineers adopting this scheme would prefer to have the busbars separated more than Fig. 10 would appear to indicate. It is probably good to recognize that many engineers have in the past objected to compound-filled metal-clad switchgear, largely because of the difficulties of changing current transformers, or of adding potential transformers to units not initially provided with sockets, etc., for these latter. These difficulties have now been practically eliminated by using a viscous oil (such as resin oil) or an oil-base compound of low melting-point for filling the chamber containing the above apparatus. It would be of interest to have the author's views on the commercial and technical feasibility of employing viscous oil, etc., for filling the busbar chambers of metal-clad switchgear for the various voltages commercially in use on this class of gear. A study of the various figures indicating metal-clad units shows that no potential transformers have been indicated. It will be appreciated that these can readily be fitted where required, and the design which permits safe

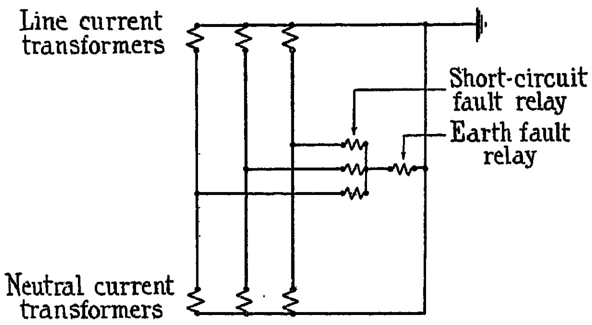

FIG. A.—Improved circulating-current protective system.

accessibility without interruption of supply to the main circuit is doubtless to be desired. Some users of metal-clad gear wish to be able to circulate current through the primaries of the current transformers for testing purposes, and to do this readily it is a simple matter to make temporary connections from a suitable local circuit through the cable and P.T. sockets. It is not clear at first sight from the author's remarks on pages 433 and 434 in regard to reactance increasing the arc energy why this should be so, and his explanation would doubtless be of interest. Referring to Figs. 14 and 15, the earthed metal divisions inside the tank can be used to greater advantage in eliminating the risks of arcing between phases and strengthening the tank if the top crosshead design of circuit breaker be adopted, as it is then possible to carry the metal divisions right across the tank. I consider that the breaking capacity of a switch or circuit breaker (mentioned on page 434) ought to be a definite figure to be stated by the maker or, preferably, by an independent testing authority. I do not appreciate the author's suggestion that the breaking capacity should be qualified by stating the basis in terms of generating plant output and reactance on short-circuit. This latter information is obviously required in estimating the short-circuit current possible, but it is not clear to me that it has anything to do with the ability of a given circuit breaker to rupture any stated power in kVA or kW. With reference to the term "stability ratio" used in the paper, should it be desired to protect more than 75 per cent of the stator winding for single earth faults without reducing the ohmic value of the earthing resistance, it is possible to do this by connecting an "earth fault" relay between the "short-circuit fault" relay star point and the current transformer star points (as indicated in Fig. A). It is true that this "earth fault" relay would require to have a setting to trip at a current less than 50 per cent of the full-load current to achieve the above protection, but it will be appreciated that such lower setting would not impair the stability ratio of the protective gear. A thoroughly sound relay can be supplied to operate with, say, $7\frac{1}{2}$ per cent of the full-load current of the generator, and this, connected as above, would give single earth fault protection on 96·25 per cent of the stator winding under the other conditions set out by the author. It will be appreciated that one of the "short-circuit fault" relays may be omitted if desired, when the "earth fault" relay is installed. This improved circulating-current protective system was, I understand, devised by one of the Metropolitan-Vickers engineers and is covered by Patent No. 144073.

Mr. P. Rosling: On page 437 the author mentions the effect on cables of a direct lightning stroke or surge. He says: "The excess voltage is absorbed in the capacity of the cable. This method, together with a high standard of insulation, satisfies the conditions prevailing in this country." It is quite true that this may save the transformer and the gear but it is not fair to the cables to make them surge arresters. If the matter is studied only from the point of view of the induced charges from lightning, which do not take place very frequently, probably no damage occurs to the cable, but if the cable is subjected to frequent surges due to switching, or other causes, trouble may arise, the crucial point being the number of times the pressure is applied before the cable will break down. On studying the question with the electronic theory of matter in our minds we see that the molecules or atoms are composed of varying numbers of electrons which presumably are arranged in varying groups depending on the element which they form. These electrons are possibly vibrating in unison with the molecules (the periodicity depending upon the temperature), and also probably moving, or able to move, in their own particular atom at a speed approximating to that of light. We know that if we bring a collection of electrons in the form of a metal bar at a high temperature near another collection of electrons in the form of paper vibrating at a lower frequency, the vibration of the molecules in the bar will transmit energy through the ether to the molecules in the paper, increasing their vibrations until the electrons in the molecules of paper rearrange themselves into the groups of electrons peculiar to carbon, hydrogen and oxygen, etc. The electrostatic field and the periodicity of vibration are

in some way connected, as we know that should the electrons be in a state of strain due to an electrostatic field, the electrons in the molecules of the paper are affected by a lower temperature, i.e. a lower rate of vibration of the molecules in the hot body, and if the state of strain is very intense the electrons in the molecules of paper are affected even when the periodicity of both sets of molecules is similar. Further, there is a possibility that if electric current is caused by the passage of electrons along the conductor, these current electrons may conceivably, as they travel at a speed approximating to that of light, jolt the groups of electrons in the molecule of the dielectric which are under intense electrostatic strain and split them up into the groups representing the elements. It is well known that in many cases of slow growth where there is apparently no law to govern the direction of the growth, as for instance in the marking on a window-pane where moisture is congealed by cold, or the growth of coral in Southern seas, the growth takes a tree-like or fern-like formation, and in examining cables after high-pressure breakdown tests, certain tree-like or fern-like marks have been found, which makes it seem possible that the intense pressure due to the peak of each alternation of the charging current has caused the electrons in the molecules of paper to split up into groups proper to the particular atoms in the molecules, and this process, having once started, has possibly localized the stress, and has continued, showing a slow growth in the tree-like marking. I would suggest that where high-tension cables have broken down for no obvious cause, the users would be well advised to put in some apparatus to act as a discharge for any high-pressure surge, say, 25–30 per cent over the working pressure.

Mr. H. Trencham: As regards most of the fundamental principles enunciated in the paper I am in accord with the author, but there are a few points on which I must join issue with him. I think that the single busbar does not provide a sufficient margin of safety. A duplicate busbar has quite a number of useful functions in connection with the operation of electrical systems, and I think that it is likely to remain. The explosion pot as a means of rupturing heavy fault currents has been mentioned, but the fact that the very first oil circuit breakers used in heavy power stations were of the explosion-pot type is rather lost sight of. There are a very large number of those breakers in use to-day, and a large proportion of them have been in service for many years. The principle of their operation is probably not completely understood, but there are sufficient data available to enable one to say that the ability of the breaker to interrupt heavy short-circuits is not a velocity phenomenon alone, and it is also peculiar that the heavier the current in this breaker the quicker the interruptions are likely to be. Moreover, the characteristic of the interruptions is very much more regular than in the other type of breaker. Another point to which I should like to refer is the rating of the circuit breakers. I think that the author has somewhat confused the actual rating of the breaker and its selection. I do not think that there can be any question that the British Engineering Standards Association intended the usual expression "kVA rating" to mean a definite number of kVA. It would be better if the rating could be expressed in terms of energy, but that is impossible. When kVA or amperes are taken as a basis, voltage must come into the question, and, as the power factor will influence the ease or otherwise of breaking, one has to assume that the very worst power factor must be taken into account, so that to express it in general terms of kVA is quite a rational proceeding. If we accept that as the rating the breaker must, in order to fulfil that rating, be able to pass a test which will give those conditions, and it is very unfortunate for the industry, particularly in this country, that very little real testing apparatus has been available. I think that one of the essential things for the switchgear industry to attend to now is to see that investigations are made with short-circuits much more comparable with those which occur in large power systems. The application of an oil circuit breaker depends on many more variables than are concerned in the action of the oil breaker itself—and those are very numerous in themselves—but to try to introduce the additional variables of the generating and distributing system into the breaker rating is a suggestion in the wrong direction. I believe that to employ bias in protective gear is the correct practice in providing for the stability of apparatus. If the relays are to be kept sufficiently delicate to function with a small amount of energy they will be liable to interruption if they have to deal with two contending forces which it is desired to balance against each other. Sound practice indicates the necessity of bringing to the relays only those tripping currents which are necessary for their correct functioning.

Lieut.-Col. K. Edgcumbe: The author suggests (rather diffidently, I am glad to see) that if economy is essential it might be gained by cutting out the earthing resistance, but I am more than doubtful as to the wisdom of this. I believe that under normal conditions about 90 per cent of all faults start as earth faults, but I imagine that with the author's arrangements 99 per cent of the faults would start as earths. In fact, I gather that this is one of his chief objects, and therefore I should have thought that he, of all people, would have insisted on the installation of an earthing resistance. The tendency of the present day to employ single-core cables in place of multicore cables—particularly for the higher voltages—serves also to emphasize the importance of earthing through a limiting resistance. The author suggests that for induced lightning discharges a length of cable should form a satisfactory discharge path. It cannot, however, do so in the case of internally produced surges, so that some form of surge gap seems to be essential.

[The author's reply to this discussion will be found on page 464.]

North-Western Centre, at Manchester, 17 February, 1925.

Mr. S. Ferguson: The need for compound-filled switchgear has arisen owing to the growth of power systems. Every extension of the high-tension distribution system has brought with it at least a proportionate number of additional faults, every extension of the generating plant has increased the severity of these faults, and the interruption of increasing values of short-circuit power has magnified the effects of voltage surges which, of course, vary directly as the value of current broken. The air clearances required to give adequate protection have increased and with cellular gear it has become practically impossible to allow the clearances which are really necessary. It is on record that flash-overs 6 in. long have occurred even on 6 600-volt systems. With compound or oil dielectric the clearances can be reduced to one-fifth and hence it is very evident that a complete compound- or oil-filled unit can be accommodated in much less space than a comparable cellular installation. Furthermore, oil and compound have a much higher dielectric spark lag against high-frequency voltages. This is a very important advantage when considering the protection of switchgear against high-frequency surges. The author has not overstated the advantages of metal-clad gear. It affords protection against dust, dirt, vermin and moisture, and explosions in the switchgear structure are eliminated as there are no air spaces in which explosive gases can collect. The maximum protection to the life of the operator is assured. It would be as well for engineers to face facts. Some time ago I analysed the Factory Inspector's reports covering a period of four years and found that 50 per cent of the accidents were due to operators dealing with switchgear which was supposed to be dead but which in fact was actually alive. Only a fortnight ago the Chief Mining Inspector's report appeared in the Press and showed that practically 50 per cent of the accidents occurred on switchgear. These facts clearly show that some form of metal-clad filled switchgear is very desirable, as it minimizes the fire risk and any damage is localized. Above everything else this type of gear is manufactured and shipped as factory-built units. I am very much in favour of standardization. At the present time the cost of switchgear is too high and this is mainly due to the multiplicity of types which are perpetuated. Metal-clad filled gear will, I believe, meet all requirements and I sincerely hope that sooner or later it will be standardized. In this connection I think that the Institution is behind the American Institute, in that there are no committees which analyse progress during the year and issue annual reports. In the American Institute there are sectional committees each of which deals purely with one section of electrical plant. For instance there is a power station committee, a protective devices committee and many others. The members consist of manufacturers and operating engineers and there is the closest co-operation. I consider that it is high time a lead was given to operating engineers on the question of switchgear if the enormous waste which is going on at the present time is to be eliminated. The objections to the earlier forms of this gear were the lack of accessibility of instrument transformers and busbars and the method of busbar selection by the change-over of plugs. The first objection has been overcome by oil filling. This is a recent innovation which has only just been put into commercial use. The outward appearance of the gear is unaltered. The second objection has been remedied by the substitution of oil-immersed selector switches or double breakers. We are frequently told that the demand for metal-clad filled switchgear is the outcome of fashion, but I think that this is an erroneous idea. There are definite reasons which have prompted numerous manufacturers in this country to spend thousands of pounds on patterns, jigs and tools for the production of this class of gear. I agree with the author when he says that the settings of protective gear are frequently too light, at the sacrifice of stability. This brings the important point that such leakage protective devices often open the short-circuit before the fault has been fully developed, and it is necessary to close the breaker two or three times before the fault can be dealt with. This makes it possible for the breaker to rupture the short-circuit power at its peak value, as the author has shown. He states that duplication should be governed by the liability to break down, and refers to immunity from breakdown. I cannot share his optimism, because duplication is governed, or should be governed, by the consequences of failure, that is, the difference it makes to the consumers who will be affected and the length of time the supply will be discontinued. There is no plant which is immune from failure and there never will be so long as it is operated by imperfect human beings. The busbars in a central station are the most immune from failure, and yet I consider that there is the greatest necessity for their duplication because of the consequences involved in a breakdown. We duplicate our transformers and feeders and I consider that it is very essential to duplicate the busbars also. The author suggests that it is preferable or more economical to increase the initial expenditure in obtaining quality and strength of parts rather than to duplicate such parts. This is not in agreement with the policy adopted towards the rest of the system and I do not see why it should be carried out on switchgear. Generators and cables insulated for 11 000 volts on a 6 600-volt system are no substitute for spare plant. I quite agree with the author that one good circuit breaker is better than two of inferior quality, provided that the inferior breakers are not able to cope with the short-circuit power, but then no breaker that cannot deal with the maximum short-circuit power should be installed in a central station. There are certain advantages attending the use of duplicate breakers and these should not be forgotten. Spare breakers are certainly useful because an attendant can ruin a breaker by closing too frequently on a fault or at too short an interval between unit-operating cycles. American manufacturers and operating engineers have arrived at an

agreement with regard to the duty cycle. The agreement provides that four operating cycles instead of two (the British standard duty) and with no time delay between cycles will reduce the breaking capacity to 30 per cent of the rated value. In other words, if the operator is going to close the breaker four times in succession without hesitation then it is necessary to install a breaker having a rated breaking capacity $3\frac{1}{3}$ times that which would otherwise be required. With regard to duplicate busbars, the author states that it is only on a few occasions during the life of the plant that the duplication of busbars may prove advantageous. He infers that it is economical to dispense with duplication. I entirely disagree because I consider that duplicate busbars are the most essential apparatus in a central station scheme. To give only a few of the uses, they provide facilities for boosting the voltage on any particular feeder, they provide means for receiving a supply from an interconnected generating station without running in parallel, and they enable non-adjacent busbar sections to be paralleled at light loads. If there is only one purpose to which duplicate busbars can be put, that is, to provide means for carrying out extensions without interruption of the supply, then I consider that there is a sufficient warrant for the duplication of busbars. The value of duplicate busbars is very much reduced if one has not the necessary facilities for making full use of them, and in this connection the method of busbar selection is important. The author advocates the change-over of busbars whilst the circuit is dead. Certainly much switchgear could be saved on our systems if it were permissible to interrupt the supply and change over the connections by hand. In my opinion this is the crudest method imaginable. When this method had to be considered a few years ago I dismissed it as impossible and agreed that nothing but oil selector switches or double breakers could be considered suitable. In the event of a busbar breakdown it is imperative that the supply should be resumed as quickly as possible, but the change-over of plugs does not allow of a speedy resumption. The advantage conferred by the use of double breakers is that the operator has complete control from his desk by means of push-buttons and there is no need to deputize another person to enter the high-tension room for the purpose of busbar selection. A separate busbar coupler is not necessary when double breakers are provided. In the case of a particularly heavy fault it is useful to have a spare breaker which can be used immediately. In an address at the International Conference, Paris, Mr. P. V. Hunter said that no serious proposals had been made to provide for automatically changing over from one busbar to the other in the event of a busbar fault. This is quite feasible with double breakers and it is possible to change over automatically in about 0·8 second. In that time I do not think that any of the synchronous machinery will fall out of step. The author is very unfortunate in his reference to Stepney and Neepsend at the foot of page 428, because the charge engineer who operated the plant at Stepney stated,* after saying that the gear was in good order: "The only criticism I have to offer is in connection with the method of putting dead the busbars when required for alterations, additions, overhauls, etc." Manufacturers ought to study the published experiences of operating engineers. With regard to Neepsend, in a discussion at Sheffield in connection with the plans for a new power station, particular interest was centred on the method of transfer of circuits from one busbar to the other without breaking load as it was wished to work some of the feeders at a different voltage from the rest. With regard to Fig. 13, the current densities given for safe ratings seem too high and I do not think that we should recommend current densities of the order of 1 600 amperes per sq. in. for current ratings of 500 amperes, especially when the British Engineering Standards Association are considering a limit of 1 000 amperes per sq. in. regardless of the temperature-rise. The author's reference to current-limiting reactors is very brief but I judge from his remarks that he is not too sure whether they are necessary. I think that the short-circuit power on a system should be limited to somewhere near 750 000 kVA by means of busbar reactors. If one calculates the enormous forces which are brought into play by short-circuits of the above magnitude I think it will be agreed that reactors should be employed not only to reduce the size of switchgear but also to protect the whole of the system. Taking the case of a 6 600-volt system in which 750 000-kVA breakers are used, the loading of the busbars at the peak of the short-circuit would be about 1·45 tons per foot run, for a 12 in. spacing of the busbars. If the supports are placed at every 2 ft. along the busbars, then the force exerted on each support would be 2·9 tons. In the case of a short-circuit of $1\frac{1}{2}$ million kVA under the same conditions the force exerted on each support would be 11·5 tons. Breakers can be built to deal with any short-circuit power but the effect of electromagnetic forces is experienced before any breaker can open. Furthermore, if the short-circuit power is not limited, the effect of surges becomes more serious. The author refers to the effect of reactance on the duty of oil breakers. I do not agree that the introduction of reactance imposes a heavier duty on oil breakers, except in outlying substations. The worst short-circuit is one at the busbars in a central station, and here the addition of 10 per cent external reactance to the 10 per cent inherent reactance will only alter the phase angle of the short-circuit current by about 3 degrees, so that the duty on the breaker in its worst location is very little increased. I agree with the author's suggestion that breakers should be selected to meet the peak of the short-circuit instead of on the B.E.S.A. basis of 6 times the aggregate plant capacity. This would give a higher factor of safety but it would add about 66 per cent to the cost of switchgear because the cost is almost directly proportional to the breaking capacity. The whole question resolves itself into this: "Is the purchaser prepared to pay extra for the increased factor of safety?" I think that the present method of stating the breaking capacity in short-circuit kVA is perfectly satisfactory and that the author's suggestion of stating the breaking capacity rating in terms of generating plant output and reactance would be a retrograde

* *Electrical Power Engineer*, January 1922.

step, as this method obtained 10 or 12 years ago. His reference to the "through" rating for circuit breakers is very opportune and I agree that such a rating is necessary, say for 1 sec. and 5 secs. This is common practice in the United States but it is rarely specified in this country. In my opinion, breakers fitted with charging resistances should be used for power transformers because I think that these resistances serve a useful purpose in reducing switching surges. On page 435 reference is made to the use of the hospital bar as a reactance tie busbar. I do not think that it should be used for this purpose as it has many other functions to perform. In selecting breakers, I do not agree with the author's suggestion that external reactance should not be taken into account in calculating the short-circuit current, as this would add enormously to the cost of switchgear. The short-circuit kVA of a 200 000-kVA station can be reduced to 650 000 kVA by means of busbar reactance. In this case apparently the author would recommend the installation of breakers rated at 2 million kVA and this would treble the cost of the switchgear. No reactance is shown between the hospital bar and the tie bar in Fig. 21. I think that it is current practice to include this and I presume that its omission was not intentional. In connection with bakelized paper condenser bushings referred to on page 437, I consider that the 1-minute test is not all that could be desired. Many bushings will stand up to the test pressure for 1 minute, but it is always the time factor which determines the reliability of the bushing. It would be much better to apply a lower test pressure for half an hour. In the design of condenser bushings for metal-clad gear it is not possible to make the male and female bushings for the plug-and-socket portion on the orthodox condenser principle, because the outer condenser layer of the male bushing is at earth potential and the inner condenser layer of the female bushing is at the line potential, so that, when the two engage, the arrangement of the condenser layers has to be arranged to suit these conditions and, in consequence, perfect grading cannot be obtained. The final design has to be a compromise between a bushing with high flash-over pressure and a comparatively low puncture pressure, and vice versa. With regard to the ring-main scheme of protection shown in Fig. 28, I should like to ask if this scheme has been put into extensive commercial use. All engineers are looking for cheaper switchgear for ring-main substations, but the scheme shown in Fig. 28 appears to be defective in that the transformers themselves are not protected. The switch fuses are apparently relied upon for protection of the high-tension side of the consumers' transformers. I cannot see how this will be satisfactory, because a short-circuit on the transformer terminals will be just as severe as one on the ring main. It is very desirable that a scheme of this sort should be available if only the above defect could be remedied. The author infers that the neutral point of a high-tension system should be solidly connected to earth. I do not think that this would be wise, because the shocks to the system would be far too great. In his conclusions he states as one of the requisites for safety and continuity, "a stable neutral point at earth potential." Does he really mean "dead" earthing? Further, I think that he could have included the draw-out feature in his list of requisites, because it is very important from the point of view of protection of the life of the operator.

Mr. T. W. Ross: Regarding the protection of generators, on page 439 the author recommends relay settings of 50 per cent, and an earthing resistance of a value which would pass twice full-load current at the voltage between phase and neutral. Such a combination would give protection to 75 per cent of the generator winding against faults to earth, and a stability ratio of 40 : 1 when using a relay which takes 0·8 VA. We went into this question some years ago and found that we obtained a much greater stability ratio when using a relay having a very much higher impedance than the relay mentioned, even with settings as low as 15 per cent of normal. As a matter of fact we can obtain a stability ratio of 70 : 1 with a relay set for 15 per cent of normal. This gives protection to 85 per cent of the machine windings with an earthing resistance proportioned to pass normal full-load current. The reason for this improvement is that the higher impedance of the relay tends to force any out-of-balance current, which may exist on heavy loads or external short-circuits, through the other alternative circuits formed by the current transformer secondary windings. By a slight modification of the connections a still lower setting can be obtained for earth faults without decreasing the stability ratio, and this method is used when the earthing resistance is not designed to pass sufficient current to give 85 per cent protection. This modification provides for one element of the relay to operate on earth faults only, and the other two elements take care of short-circuits between phases. I agree with the author that the value of the earthing resistance is very often too high, but the operating engineers in this country insist on a high earthing resistance which of course necessitates lower relay settings than are desirable. In this connection we very often find that when we have to supply a generator which is controlled by switchgear of another make, the protective gear does not give sufficient protection and lower relay settings are necessary. A difficulty arises here, as unless the gear is well designed and carefully manufactured, insufficient stability results. With regard to the protection of feeders, I agree with the author that the tendency is to have relay settings which are too low. To my mind the protective gear for feeders is most useful in maintaining a continuity of supply and not so much in preventing damage to cables. If, therefore, this object can be realized with relay settings comparatively large, there is no object in impairing the stability of the system with low settings. In the past, and even to-day, certain engineers when purchasing switchgear or protective gear place too much importance on the sensitivity of relays or protective systems. The system of inertia relays described by the author is very ingenious, and I would suggest that if relays having a slight inverse time-limit characteristic were used on balanced protective schemes very many of the troubles due to abnormal transient conditions would be overcome. Such relays could also be shunted by non-inductive resistances to provide a by-pass for high-

frequency capacity currents which may exist in the main cables due to surges. The author mentions time-lag devices for use as discriminative protection on feeders. Such protection is certainly not ideal, but one is very often faced with the necessity of an alternative to the expensive instantaneous balanced protective gear which requires special cables or pilot cables, and something of this nature then has to be resorted to. It is a well-known fact that a short-circuit will soon cause synchronous machinery to drop out of step, and it is here that time-lag devices have their limitations. Some years ago there was a referendum of the operating engineers in America in order to come to some agreement as to the length of time for which it was possible to hold a short-circuit, and it was then decided to allow a maximum time-lag of 2 secs. It is therefore apparent that this maximum time of 2 secs. must be split up into fractions of a second if several circuit breakers are in series. This means an accurate type of relay which will discriminate with different time settings of a fraction of a second. A very good type of relay for this purpose is an induction relay having inverse time-lag characteristics and so designed that for heavy overloads the time-lag becomes approximately of a definite value. Such relays can be obtained with a maximum time-lag of not more than 2 secs. on short-circuit and this can be split up into 4 or 5 equal parts for switches in series. If, in addition to overload settings, directional features are added, protection can be obtained for ring mains, parallel feeders and supply networks. This form of protection is very largely used in America and on the Continent. I agree with the author that reverse-power relays are practically useless for the protection of generators. Some engineers contend that they should be added to take care of a failure of the prime mover, and it is possible by suitable connection to use such relays to protect against failure of the generator field, but on the whole I think that it is best to leave them out. I was interested in the lantern slide which shows an emergency trip situated near the machine. I consider that this is a very necessary feature where the machine may be some distance from the control board or in fact may be in another room. The engine driver would then have some control over the machine in the event of trouble with the prime mover, and this is much better than reverse-power relays. I cannot urge too strongly the need for rapid isolation of a faulty generator and in this connection I do not agree with the author that the tripping of the automatic field switch should take place after the main switch has opened. We made a number of tests to prove that it was preferable to trip both switches simultaneously, and we believe that it is necessary to do so. This was fully discussed in Mr. Kuyser's paper * before the Institution. I do not understand Fig. 37, as I cannot see why the automatic field switch should not be operated as a routine test. In regard to the balancing of protective transformers I should like to know whether the author experiences any difficulty in maintaining a balance on the transformers when they are eventually mounted in the cast-iron housing. We find that it is difficult to get a perfect balance when the protective transformers are supplied by other makers to fit in our ironclad gear. This is, of course, frequently necessary when the switchgear at both ends of a feeder is not of the same make. I am sure that metal-clad gears will have a great future, but a note of warning which I would give to operating engineers is that simplicity is essential to success. We have been used to what we call facilities in the open-type gear of the past, but these facilities are perhaps not so easy to obtain in the metal-clad gear. I believe, however, that the other advantages much outweigh the loss of what is very often an unnecessary feature.

* *Journal I.E.E.*, 1921, vol. 60, p. 176.

Mr. H. A. Ratcliff: The author refers to the risks to continuity of supply arising from the unnecessarily sensitive settings of protective relays, and there is no doubt that within reasonable limits the higher the settings the greater the stability of a system. Modern plant should be capable of withstanding momentarily very considerable overloads. Metal-clad reactances appear to possess some distinct advantages, and they are a natural corollary to metal-clad switchgear, but their use involves some incidental difficulties. The effective earthing of the metal sheathing—usually lead—is a matter of considerable importance, but the best method of effecting it is by no means obvious, since provision must also be made to prevent troubles arising from the comparatively high pressures which may be induced in the metal sheath. It is essential that reactances should be absolutely reliable, since they are intended as the final safeguard in the event of severe short-circuits occurring on a system, and therefore it hardly appears desirable to adopt a form of construction which possesses all the inherent weaknesses of cable, further accentuated by the severe conditions arising from electromagnetic forces and induced E.M.F.'s of considerable magnitude. Although I am in agreement with much of what the author says on the subject of duplicate busbars and change-over facilities, I am nevertheless of the opinion that he rather underrates their advantages. In connection with substation operation more particularly, there are occasions when it is very convenient and even desirable to be able to change a circuit over from one source of supply to another without interrupting it. The separation of the phases in e.h.t. metal-clad switchgear appears to be a matter of very great importance, and without such separation it is by no means evident that metal-clad gear would be in any way superior to cellular gear in the event of an internal short-circuit occurring between phases. In fact the resulting conditions in the case of metal-clad gear might be the more severe owing to the incidental dangers arising from the destructive distillation of the compound filling. The analogy with three-core cable is hardly applicable, since cables are invariably protected by automatic devices, whereas the protection of busbars is unusual and frequently impossible. The reference to the use of explosion pots on the contacts of circuit breakers is very opportune. If explosion pots are all that is claimed for them, and they are used as an additional line of defence, well and good, but if they are merely fitted in order that inferior and mechanically weaker tanks may be employed, then the principle cannot be too strongly condemned. I am in agreement with the author's views on the B.E.S.A. method of

determining the necessary breaking capacity of oil switches. In the case of switches employed on large interconnected generating and transmitting systems there appears to be little, if any, justification for the B.E.S.A. method of computing the switch ratings. In this connection it would appear that actual switch ratings are very elastic, and consequently a switch may have its rated breaking capacity increased from 150 000 to 250 000 kVA within a period of a few days, presumably on the strength of its observed behaviour under known operating conditions. The whole subject of switch ratings, however, still calls for full and careful investigation and standardization. Charging resistances incorporated in the construction of circuit-breaker moving contacts are most unmechanical, and therefore undesirable; but unfortunately experience has shown that they are at times necessary in order to protect the end-turns of machine stator windings where no other form of protection is available, and also more usually to prevent the inadvertent operation of protective gear of the balanced-current type. It is probable that with modern plant having the end windings properly reinforced, and with thoroughly stable protective and overload devices having reasonably high settings, charging contact resistances are not really necessary. The author's remarks on the subject of reactances are very apposite as there is no doubt that the indiscriminate employment of reactances may be easily overdone. Reactances should be employed not so much for the purpose of permitting the use of switches having a smaller rupturing capacity than would otherwise be necessary, as for preventing enormous concentrations of energy in the event of short-circuits occurring in, or in the immediate vicinity of, generating stations, and also for minimizing the effects of such drastic disturbances by enabling the pressure on other portions of the system to be maintained above the value at which synchronous plant falls out of step. Reference to current transformers of the single primary turn or bar type was inevitable in a paper of this description; within their limitations there is much to be said for them, and they possess undoubted advantages, but it is essential to recognize their limitations. The single-turn type of current transformer is most desirable for use on e.h.t. circuits, but unfortunately these are usually just the circuits for which it is least suitable owing to the comparatively low values of the primary currents. As a general rule, current transformers of this type may be used with advantage for ammeters and overload relays, but except on heavy-current circuits they are useless for watt-hour meters, and unreliable for protective gear of the balanced-current type. Core-balance methods of protection, where possible, afford a reliable means of overcoming the inherent defects of single-turn current transformers in this respect. The value of so-called high-frequency surge arresters is, to say the least, open to question, and certainly on an underground transmission system the cables themselves form the best possible high-frequency surge arresters. The danger attaching to the use of oil-immersed isolating switches is not perhaps always recognized as it should be, and therefore the author's reference to the subject is particularly appropriate. I cannot agree with the author that there should be no resistance at all in the connection between the neutral point of a high-tension system and earth, since every earth fault would then amount to a short-circuit with all the usual incidental effects. Moreover, the resulting damage at the fault would be very much greater, and the effects of the heavy earth currents might be most serious in other respects. The essential requirement of the neutral earth connection is that its resistance should be sufficiently low to ensure the reliable operation of the various fault protective devices on the system. I am in complete agreement with most of the author's remarks in regard to cable protective gear, and observe with interest that he now fully appreciates the importance of the transient capacity currents in the main cables, quite apart from the effects of the capacity currents in the pilot conductors. The non-inductive shunting of protective relays has been adopted with a considerable measure of success on the Manchester 33 000-volt system. The protective scheme illustrated in Fig. 32 is very ingenious and should be quite effective; but the discriminative bias by means of relays possessing different time characteristics is undoubtedly the weak feature. The real value of the quick-acting relays probably lies in the fact that they constitute a permanent load on the current transformers, with the result that the pressure applied to the pilot cables is reduced, and if transformers of the closed-core type are employed, the lower saturation in the cores due to the secondary load enables the transformers to be balanced more accurately. The objections to the Hunter four-core system of cable protection are the apparent unbalanced capacities of the three phases to earth and the necessity of making all joints core to core, since in practice this is extremely difficult and in some cases almost impossible.

Mr. D. R. Davies: After several unfortunate experiences and shut-downs, due to overrated and out-of-date cellular gear, some operating engineers are now looking hopefully to the metal-clad type. The author speaks feelingly of the troubles peculiar to open-type gear, and it would add considerably to the value of his paper if he would also record the troubles experienced with metal-clad gear. The manufacturer rarely has a free hand in obtaining sufficient space for his switchgear, and it is not right to condemn cellular gear because of troubles experienced with a layout squeezed into an existing building. I know of three disastrous fires which have occurred in switch rooms during the past 12 months, and it is rather significant that all of them were equipped with Continental switchgear. Interlocks are very simple and cheap for metal-clad gear of the draw-out type, but they become very complicated on designs having oil-immersed selector switches similar to those shown in Figs. 7 and 25. It is no easy job, for example, to design simple interlocks which will ensure that all contacts within an oil-immersed busbar selector switch are dead before the removal of the tank. Interlocks on large cellular layouts are also fairly expensive, because when required it becomes essential to operate all isolators and selectors by a remote mechanical drive. Perhaps the best feature of metal-clad gear is the ease with which the circuit breaker

can be withdrawn in case of emergency from one circuit and plugged into another. In fact, American manufacturers are now supplying breakers for cell mounting built on a carriage in order to incorporate this feature. Whatever may be our individual views on the necessity for changing over the breaker from one busbar to another without interrupting the supply, the fact remains that this is possible with cellular gear and further does not involve additional complications in the layout, or incur additional expense. The majority of supply undertakings requiring metal-clad gear do not regard the necessity for changing over on load as important, and in the few cases where the purchaser insists in this feature he must be prepared to pay more for the metal-clad type. It is safe to say that 90 per cent of the supply undertakings in this country would be prepared to accept metal-clad gear which would not permit changing over from one busbar to another on load. The manufacturer is not therefore justified in increasing the cost of a design which is almost universally acceptable. It occurs to me that the class of operator who would open an isolator on load and cause a large station to be shut down three times in one year is just as likely to forget to change over all the plugs on the metal-clad gear shown in Figs. 8 and 14. This may result in the accidental coupling of busbars, and I think therefore that an oil switch as shown in Fig. 14 should be provided with an interlock which prevents the switch being racked home on the bars with the plugs incorrectly inserted. Of the schemes submitted by the author for changing over on load, that shown in Fig. 10 using two breakers is the best but is expensive and requires double the floor space. The author's idea that it is better to spend money on one good breaker instead of two of inferior quality would not be very convincing to an engineer who regarded continuity of supply as his main object. The factor of safety of the oil circuit breaker should obviously be the same no matter which scheme is adopted, so that if an operating engineer decided that one breaker would give him the desired flexibility he would hardly be justified in buying a rating exceeding his requirements simply on the score of increased security. If the author's point of view is correct it would be better on a 6 600-volt system to lay one 11 000-volt cable for a feeder instead of running two 6 600-volt cables in parallel, in order to obtain a greater factor of safety on the cable insulation. For two reasons it is not good practice to put two switches into one tank as shown in Fig. 11, viz. (1) when the switch on the right opens, the inner arc is blown to the left across the centre contact, and when the switch on the left opens, its inner arc is also blown across the centre contact, and (2) the tank is always eccentrically placed in relation to the arcs from which the explosion is initiated, and the interruption of a severe fault may cause the tank to be displaced sideways. I should like to ask the author whether he regards the design of breaker shown in Fig. 7, which has a single horizontal break, as being superior to one having two vertical breaks in series. The single horizontal arc is formed substantially parallel with the surface of the oil, and on a heavy fault one would reasonably expect the magnetic field to blow the arc upwards with such violence that it would extend beyond the oil-level in the tank, whereas in the conventional double-break switch as both arcs are drawn down deeper into the oil this must reduce the risk of flame emission. Moreover, using the same depth of tank it would be possible with a two-break switch to double the head of oil above the arc, which would not only reduce the risk of flame protrusion but also provide better facilities for cooling the liberated gas before reaching the oil-level. It would be interesting to know whether the construction shown in Fig. 7 has given satisfaction in service and, further, if this particular design of breaker has actually interrupted faults of any magnitude without showing signs of distress. The number of double-break switches which are meeting their guarantees are so numerous that responsible engineers and manufacturers should regard any distinct departure with diffidence. Moreover, different ratings of the double-break type were tested at Baltimore and proved their suitability for dealing with large amounts of power. The testing facilities at the disposal of the British switchgear manufacturer are far too limited. Even the fortunate ones, who also make large machines, can only rely upon a maximum of 200 000 kVA being available when it is desired to test out a circuit breaker. We are therefore forced, when considering the possible performance of the circuit breaker on a large system, to rely upon the data obtained from field tests carried out in America. I fully appreciate the excellent work done by the British Electrical and Allied Industries Research Association, but however convincing their final recommendations may be, we shall still lack the testing facilities necessary for proving the possibilities of the super-station circuit breaker, until the supply undertakings in this country realize the mutual advantages of co-operation with the manufacturer. The author shows very clearly in Fig. 18 the various values of current which a breaker may have to interrupt on short-circuit. The chances of a fault developing and reaching its maximum value at the exact moment at which the arc-tips separate are very remote. For example, if the arc-tips were to separate 0·02 second later than the point C in Fig. 18, the current to be broken would be 14 instead of 20 times full load. I think, therefore, that the author is perhaps unconsciously providing an excuse for a weak breaker failing to do its duty. There seems to be a tendency, both by some manufacturers and also by supply undertakings, to take the British Standard Specifications too literally. My experience has indicated that the various clearances, lengths of insulators, etc., recommended are, as stated in the Specification, minimum values. The breaking capacity of a circuit breaker has no reference to any particular system and the breaker is sold by the manufacturer for a specified current and voltage. The effect of reactance or power factor, or its probable position in any particular system, should all be considered carefully by the designing engineer before deciding on its short-circuit rating. Sometimes a purchaser does not state in his specification the breaking capacity required, but gives instead the plant capacity of the station and leaves the manufacturer to offer a breaker which he considers suitable for the conditions. In these circumstances it is necessary

for the manufacturer to state in his tender the assumptions made in arriving at the short-circuit current to be interrupted. Otherwise the buyer may assume that the circuit breaker is capable of dealing with any value of the short-circuit current. Whether a circuit breaker will withstand the repulsive forces due to "through" currents of the order of 100 000 amperes or more, depends mainly on the design of moving contact used. The insulators surrounding the stems are analogous to cantilevers with a distributed load, and apart from their inherent strength to resist the repulsion it is safer to use a brush, which effectively locks the ends of the stationary contacts together, in order to prevent deflection. One type of moving contact which is capable of locking the ends of the stationary contacts together, and also increases the bedding pressures of contact as the current increases, is the "Y" brush, shown in Fig. B herewith. This brush was developed in the

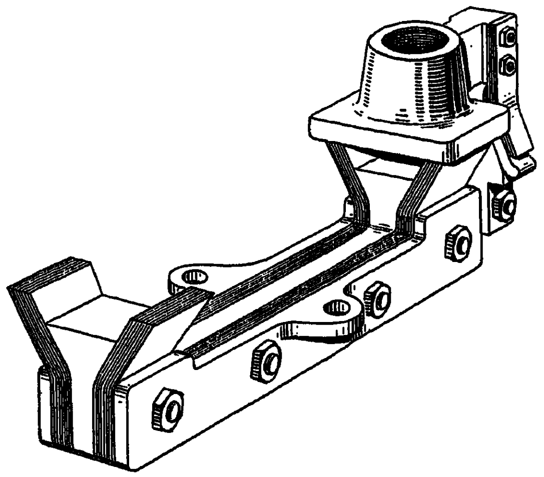

FIG. B.

United States by one of the leading manufacturers and, after exhaustive tests had proved other types unsuitable for withstanding the passage of large "through" currents, completely justified the claims made by the designers. At that time American engineers were considering the advisability of rating oil circuit breakers on the 5-shot basis. To meet such a rating the breaker would be required to interrupt its guaranteed short-circuit current five times in succession and then be in a condition to carry its rated load continuously. Subsequently, breakers fitted with the "Y" brush were tested at Baltimore and interrupted arc currents of the order of 20 000 amperes (R.M.S.) at 13 000 volts seven times in succession. Even on the last shot the current transferred from the main path to the shunt path through the arcing contacts without causing pitting or welding on the brush face. It is doubtful whether such a performance would be realized with finger contacts as used for the switch shown in Fig. 14. Although finger contacts increase the bedding pressure on the moving element with increase in current, this increase in pressure is not sufficient to lock the ends of the stationary insulators together and prevent them splaying outwards as the "Y" brush does. I should like to mention incidentally that the repulsive forces are always greater in an oil circuit breaker than those calculated by means of the usual formulæ, because in deriving the well-known expressions no allowance is made for the increase in flux due to the presence of the tank. In certain cases where a circuit breaker is fitted with a rectangular or elliptical tank, the throw-off force may be as much as 50 per cent more than would be obtained by neglecting the presence of the surrounding iron. I am surprised to note from Fig. 14 that the author advocates the use for metal-clad gear of what are apparently porcelain insulators. These insulators are liable to crack when filling the hoods with hot compound, and such cracks are very difficult to detect, even with a high-pressure test. Further, if a porcelain becomes badly chipped or cracked in service, the complete hood must be returned to the manufacturer to have the damaged insulator replaced. Bakelite insulators have the great advantage of not being brittle, and although of course they are liable to surface damage by careless attendance, this can be repaired on site with far less inconvenience and expense to the purchaser. However much care is taken in producing a reliable potential transformer, and whatever test the manufacturer is prepared to subject his product to, operating engineers will always insist on the provision of fuses on the high-tension side. I believe I am correct in assuming that the metal-clad gear in Fig. 7 accommodates the potential transformer and its fuses in the oil-immersed feeder isolator tank. Consequently, it is necessary to open the oil circuit breakers at each end of the feeder, or, in the case of a generator, cause a complete shut-down before the transformer or its fuse is rendered accessible. This arrangement is so inconvenient that I think operating engineers are justified in demanding metal-clad gear, which enables inspection of the potential transformer and makes re-wiring of the fuses possible without causing interruption to the supply.

Mr. P. B. Hall: I quite agree with the author that the term "foolproof" which is sometimes applied to electrical apparatus is a misnomer, but it is extremely difficult to make apparatus so mistake-proof at commercial prices that it cannot be deliberately abused or used incorrectly. On page 426 the author advocates all-metal enclosure for all electrical apparatus, even up to lighting fittings. This is very good theoretically but is not very practicable, and in any case would be too expensive for the vast majority of installations. On page 427 he refers to the "development of metal-enclosed switchgear," but I do not agree with his assumption that the air-insulated types, or in other words the cubicle and truck types, are a "half-way measure." As regards these and their "safety factor" (which is the main point), the act of withdrawing the truck from its container in most cases isolates right back to the busbars, due to the intervention of shutters, while cubicles, at any rate so far as my firm are concerned, are always interlocked so that the contacts back to the busbars are dead before the door of the cubicle can be opened. As regards such interlocking, about nine months ago I was in a new power station which had a large installation of high-tension switch cubicles without an interlock anywhere, so that once

anyone was in the switch room he could at any time open the door of a high-tension cubicle and walk inside. This I consider to be bad practice. There are advantages and disadvantages in filling in busbar chambers solid with compound, but I consider that the disadvantages frequently outweigh the advantages, and there is a great deal to be said for the greater accessibility of the cubicle or truck type of gear for very high capacities and voltages in the event of faults, and in this connection I think that the words "the distinct inaccessibility of every conductor" which the author claims for the compound-filled gear are rather an unfortunate expression. Referring to the "metal-clad switchgear construction" mentioned at the foot of page 427, the author gives three types of isolation, namely, horizontal, upward and downward types. In the downward type of isolator—with which the author credits my firm—the live socket contacts in the isolating chamber are also deeply recessed just as they are on the horizontal type to which the author refers, and the isolating jaws before insertion into the isolating contacts are passed through slots in an insulated shield. In the illustrations of the three classes of the horizontal, upward and downward isolation, which the author shows in Figs. 4, 5 and 6, and which he says are diagrammatical of classes only, Fig. 6 shows the downward type referred to above. He also shows each type having the busbar chambers filled with compound, but I certainly do not agree with him when he says (see page 427) that these metal-clad types of switchgear are generally of the solid type—if by this he means having compound-filled busbar chambers. In spite of all the tests made on such alternators as are available, a great deal still requires to be done in respect to fixing the kVA breaking capacity of switches for commercial use. Although I agree with the author's remarks in regard to insulation troubles on page 437, unfortunately the trouble is that whilst most of us are continually improving insulation, and thereby as a rule incidentally adding to our costs, the user generally objects to pay more for the gear.

Mr. A. Bannister (*communicated*): While the growth of metal-clad switchgear has no doubt been fostered by the extreme "safety first" attitude adopted in this country towards anything electrical, it can also be claimed that the space limitations imposed upon switchgear designers by those responsible for station layouts have also been a factor in promoting this growth. For years past, the switchgear engineer and designer has been endeavouring to squeeze, as it were, a quart into the pint pot allowed to him. Metal-clad switchgear, whether of the truck, steel cubicle or armour-clad type, is the result, as this gear includes the maximum of safety with a minimum space requirement. It has its limits, however, and for voltages over 35 000 it is very doubtful whether metal-clad gear is possible until our knowledge of solid dielectrics and the voltage stresses therein under operating conditions is increased. For some time to come, open-type gear relying mainly on air and porcelain for insulation will be used above this limit. After all, these two insulators are the cheapest available and probably those about which most information is available. While the tendency has been for switchgear to move towards metal-clad types, it is interesting to note a movement in the opposite direction; this is in the case of reactors where the oil-immersed iron-core reactor has been largely superseded by the open-type concrete reactors, and here again space requirement has been one of the deciding factors. I cannot agree with the author's implication that the duplication of parts is governed by the liability to failure. While in some cases this may be correct, there are other cases where the question of duplication is decided by the operating conditions or requirements of the system layout not connected with any possible failure of apparatus. For example, I am aware of one large power station where the testing arrangements were such that the provision of duplicate busbars was practically necessary to enable machine tests to be carried out. Where duplicate busbars are provided, the question of circuit change-over without interruption of supply has to be considered. The author considers this to be an imaginary necessity in the majority of cases, but here again I suggest that this requirement depends on layout and conditions. While duplicate supply to outlying substations may be usual on large interconnected systems, it is probably exceptional for the general run of smaller systems in this country, and in the latter cases, if continuity of supply is to be maintained, some change-over device without circuit interruption is essential on the outgoing feeder circuits. The arrangement shown in Fig. 11 is not a very satisfactory one as the central main contact is in an unsuitable position. Apparently the main contact of one switch becomes the arcing contact of the other, an arrangement that is hardly to be recommended. On page 429 it is apparently hinted that there are cases when a busbar coupler switch is not required. This can only occur when the busbars are paralleled through the isolators or similar devices. When this is not possible a coupler switch is essential, especially if duplicate supplies are given to substations, otherwise there is the possibility of paralleling bars out of synchronism through substation connections. We cannot safely say that any particular type of apparatus is free from insulation failure. If such a failure occurs the duration of any arc formed will depend on the position of the fault or the sensitiveness of the protective gear. If the failure is outside the protected zone one is inclined to the view that the arc is likely to continue for a long period and that more damage would result to metal-clad compound-filled units than to the other types, due to the positive metal-to-metal circuit and the inflammable and conducting nature of the vaporized compound and metal. If complete separation of the phases in different floors or buildings does not prevent phase-to-phase faults, as stated, it can hardly be expected that metal-clad switchgear with its close spacings will be free from similar troubles. The subject of circuit-breaker rating and design is worthy of a paper to itself. While there are still many points to be learnt about breaker operation under fault conditions, several known points are often overlooked by users and designers. While agreeing with the author that failures have been due to mechanical weakness, these have more probably been caused by secondary explosions

and not by the immediate results of the rupture of the circuit. Records of short-circuit tests carried out a few years ago, where powers up to 500 000 kVA were interrupted, showed that the pressures recorded near the contacts varied between 100 and 150 lb./sq. in., but when a secondary explosion occurred a value of over 600 lb./sq. in. was reached. Dr. Garrard in a recent article showed the danger of these secondary explosions and pointed out that not only is the resulting pressure 3-4 times that due to arc energy but this higher pressure is generated in a much shorter time, thus rendering it doubly dangerous. In one case while the arcing period was 0·02 sec. the pressure due to a secondary explosion reached its maximum in 0·004 sec., 0·014 sec. after the rupture of the circuit. It is the latter effect that should be remembered, and the object of the designer should be to design the breaker so that when interrupting its rated short-circuit kVA there should be no possibility of the mixture of gases above oil-level being fired by the arc of rupture. Mention is made of speeding up the velocity of the contacts to reduce arc energy, but it is often overlooked that the throw-off forces due to electromagnetic repulsion resulting from large fault currents are generally far in excess of any mechanical loading of the moving element, and these will probably decide the speed of break under fault conditions. Mechanical loading should only be used to give quick operation under normal conditions. A single tank with steel phase barriers tends to increase the mechanical strength of the breaker, but care should be taken to ensure that the tank is equally strong in all directions. The design illustrated in Figs. 14 and 15 appears to be weak to some extent both electrically and mechanically, owing to the fact that the phase barriers are not continuous through the tank. I am pleased to note that the author deprecates the use of charging resistances. They are a constant source of irritation to designers and it often appears to be overlooked by users that these resistances increase the impedance of the breaker during fault conditions. As their thermal capacity is small they are likely to cause trouble in such cases. On the subject of rupturing capacity (see pages 432 and 433) the author is surely confusing the actual rupturing capacity of a breaker with the rupturing capacity required of the breaker when used on a particular system. This confusion is apparently due to the fact that rupturing capacity is being talked of in terms of plant capacity, a practice which is not to be recommended. As far as we can tell at present, the short-circuit rupturing capacity of a breaker is a fixed value in amperes under prescribed conditions. The proposed American standard specification recognizes this and states the breaking capacity to be a certain number of amperes at a definite voltage. The B.E.S.A. specification combines the same current figure with the rated voltage of the breaker and the circuit constant to give a kVA value, a figure from which an attempt is being made to rate the breaker in terms of plant capacity. With this fixed rating, the question of the size of breaker to install on a given system is one for the operating engineer, who must balance the possible risks against costs. He can either install a breaker rated to interrupt the fault current at D (Fig. 18) and chance its failure to do so should it operate at the point C, or pay the additional cost for breakers rated to interrupt the larger current. If the first alternative is taken, the design of the breakers must be such that they will withstand the mechanical forces due to the current at C. As in practically all cases the application of breakers is based on the lines indicated in the appendix to B.S.S. No. 116, present-day breakers are designed to meet this requirement. The confusion of actual rupturing capacity with the application of breakers for a given plant capacity suggests that the question of the duty cycle of oil circuit breakers is not clear; it would therefore appear desirable to have a more definite statement on this point than Clause 52. The suggested American standard specification would form a very good basis upon which to start. Dealing with other components, very probably most engineers will agree that the bar-primary current transformer is the best type to install on large systems, but many operating engineers still require manufacturers to attempt to reconcile small current-capacity designs of this type with B.E.S.A. specification requirements for ratio and phase-angle errors. Excess-pressure dischargers present a problem on compound-filled metal-clad units if required, but these are usually omitted on cable systems. Arresters for overhead lines should be placed outside the station as they are practically part of the line equipment. The use of cable as a type of condenser arrester may be satisfactory in this country where lightning storms are infrequent and not severe, but such a device could hardly be considered efficient for the severe lightning conditions in other countries. Incidentally one would like to hear the cable maker's comments on this practice. The arrangement illustrated in Fig. 27 is a very cheap scheme for controlling the high-pressure side of a small transformer, but it would be interesting to know what happens when a fuse has to be replaced in wet weather. Although the lid may be replaced in a short period the water that would enter the case would seriously reduce the electric strength of the oil. In the various schemes of protective gear no mention appears to have been made of the modification of the Merz-Price circulating-current system patented some four years ago. This modification consists of the connection of a relay between the usual relays and the earth lead of the circulating-current system. This scheme permits of a coarse setting for the phase relays and, with a standard leakage relay, approximately 95 per cent of the winding is protected against earth faults. In conclusion, the simplification of protective schemes seems to be desirable as the variations of the balanced principle are becoming numerous with a gradual increase in the number of parts required.

Mr. S. R. Mellonie (*communicated*): The most singular feature of the paper is the omission of any reference to potential transformers. The title certainly covers these components, and it may be asserted without fear of contradiction that more trouble is caused by the breakdown of potential transformers than of current transformers, to which considerable space is devoted. The rupturing capacity of the fuses used to protect the h.t. side of these instrument transformers is round

about 2 000 kVA, being somewhat higher for the carbon-tetrachloride fuse with spring-accelerated break, and less for the dust-filled fibre-tube type on lower voltages. The expulsion type of fuse has an intermediate rupturing capacity and a distinct advantage over both, inasmuch as re-wiring is a simple matter. The location of this type demands careful consideration, however, as flame is expelled during the operation. These figures emphasize the necessity of providing current-limiting devices to enable the fuses to deal with faults to earth or between phases. Resistances are available in the form of a composition rod with a carbon-silicon base, and would appear to be an attractive proposition. Unfortunately these are not reliable, tests showing erratic variations in resistance after service.* These rods are also very brittle, and instances are on record where the cost of replacement due to breakage is unduly high. Such difficulties have led to the development of wire-wound resistances for this service, and quite simple designs have proved successful under "dead short-circuit" tests. On systems up to 37 kV the value of the ohmic resistance as determined by the limitation of the fuse is always so low that the question of interference with the regulation of the transformer does not arise. A rating of 0·1 sec. has been found quite suitable and during the test the wire glows red, the temperature being between 600 and 800° C. To obtain the requisite thermal capacity, the current density for a given material is limited, and this fixes a minimum length of wire for a given voltage, irrespective of the diameter of the wire. Another point deserving more attention is the size of wire used for the primary windings of potential transformers. Many designers use No. 40 S.W.G. (0·0048 in. dia.) wire, and it is open to question if this can be justified as an engineering proposition. The slight increase in cost and bulk of a transformer using, say, 0·01 in. dia. wire would be more than compensated by the increased reliability. The specification and adoption of 0·01 in. or 0·02 in. dia. wires as a minimum would seem to be desirable. Several cases have occurred where elaborate and expensive protective systems have failed to function due to the trip coil being open-circuited, and this is a serious matter. In all these cases the coils were wound with wire less than 0·01 in. dia. The majority of modern oil circuit breakers are tripped by the excitation of separately supplied trip-coils, and this method has several advantages. The coil does not normally carry current and so consumes no energy. Owing to the short time rating a small coil gives the necessary blow to release the mechanism. It does not, however, fail to safety. This desirable characteristic can easily be obtained by the use of tripping mechanism with a no-volt feature, the various protective relays being arranged to open a coil circuit which releases a weight or catch to trip the switch. This method is not in favour at present and has several disadvantages, but possesses the distinct virtue that any failure becomes obvious.

* Compare curves published by Steinmetz.

[The author's reply to this discussion will be found on page 464.]

South Midland Centre, at Birmingham, 18 February, 1925.

Mr. W. Wilson: I am in agreement with the correctness of the "stability ratio" for estimating the value of protective gear. This implies that, first, the gear must be stable for all external short-circuits that can pass through the equipment, up to, or even exceeding if necessary, 20 times the normal value of the load. When this condition has been fulfilled, the sensitiveness of the operation for fault currents must be as great as can possibly be obtained by the designer. The author appears to deprecate the use of fine fault settings as being unnecessary for efficient protection, and from the figures quoted in the case of feeders, viz. 2 to 3 times normal full-load value, it would seem that a very low standard in this respect is advocated, and I think that a few words upon this point will not be out of place. If the case of transformer protection be first considered, it is not difficult to ascertain the degree of sensitiveness for this type of apparatus, and to demonstrate that it should be a very high one. First, there is the condition that the relays must not be operated by "through" currents of about the order specified, i.e. about 20 times normal full load. Secondly, the other limit is determined by the magnetizing current of the transformer, which at no load and light loadings is the preponderating current passing into the transformer. Since it does not pass out again, it behaves exactly as a leak would do, so far as the protective gear is concerned, and the protective equipment must be so designed that this current is not capable of causing operation. Now the magnetizing current for a modern transformer is in the vicinity of 5 per cent, and thus the lower limit of fault setting is obtained. There is a very strong reason why the sensitiveness should be fixed at this limit if it can possibly be managed, as transformer faults in nine cases out of ten begin as leaks between adjacent turns of the same phase. Such faults upset the balance very slightly, and, with relays that are unable to trip at this small degree of unbalance, the fault has to continue burning the insulation until it has reached sufficiently large proportions to cause operation. The continued destruction of the windings of so important a piece of power equipment as a transformer is an event to be avoided to the utmost extent, since it not only increases the element of danger to life and property but also much increases the length of time over which the apparatus is out of commission for repairs. Thus the characteristic of the ideal protective relay can be deduced. It constitutes a curve which is only slightly above the minimum of 5 per cent at no load, remains approximately horizontal until normal load has been passed, and thereafter trends upwards at a sufficient rate to be above the instability point at all degrees of overload. This characteristic, as far as I know, can only be obtained in its ideal form by a biased relay provided with a correct counterweight. By virtue of the bias the sensitiveness

of the relay is decreased, as the load rises, by the automatic restraint imposed by the biasing arrangement, and thus stability at overloads is obtained. By virtue of the counterweight the fault setting is raised as much as is desired at no load and light loadings in order to bring the curve sufficiently above the magnetizing-current point to prevent operation. Dealing now with alternators, it is evident that the finest setting consistent with stability is appropriate in this case also, for the modern turbo-alternator possesses all the elements of a blast furnace except the means of ignition. Once the latter has been effectively provided, and failing adequate protective devices, a period of only about 10 seconds is required to bring about the entire destruction of the machine windings. Manual methods are thus useless for isolating the machine, and not only is automatic protection essential but it must be as sensitive as possible in order to reduce the amount of energy that can be concentrated in the destruction of a portion of the windings without being able to trip the relay. Even if the setting of the relay be as low as 20 per cent it will be seen that in the case of a 10 000-kW alternator it is still possible for destructive energy of over 600 kW per phase to be employed in setting fire to the insulation without any protection being given. The case for a sensitive setting is equally strong with regard to feeder protection. The author has assumed that cable faults always come on suddenly, and that a sensitive fault setting is unnecessary. This, I think, is not quite an accurate description of what actually takes place. It is true that when mechanical damage occurs to a cable the fault usually comes on suddenly, although even this depends upon the extent of the damage. It is quite otherwise, however, with regard to electrical faults, which include those that may be caused by overheating the cable, by overstressing the insulation in some way, or by faulty manufacture. In any of these cases the fault originates as a weak spot in the insulation, and is actually a high-resistance leak which gradually develops into a complete breakdown. It is a fact that by the use of sufficiently sensitive relays such a fault can usually be detected several hours before the breakdown occurs. Not only therefore is it possible, by the use of sensitive relays, to remove the faulty section before any extra damage is done, but the severe shock to the system which occurs when a complete breakdown is experienced is also prevented. I think that these facts will show that the advantages attending the use of a sensitive protective scheme, possessing stability at the same time, are very real ones. I was much interested in the "diverter" relay, shown in Fig. 32, for decreasing the sensitiveness at overloads. It would appear, however, that the restraint added by this relay is of a rough description as compared with that given by the biasing principle, which is able to apportion the restraining effect exactly to that required at each value of the load. In addition, I consider it very undesirable that when a single relay is capable of doing the work, two of these should be employed. The use of unnecessary relays and electrical contacts in power station apparatus should, I think, be avoided at all possible cost. The second point which I propose to raise concerns the reference to the split-conductor system on page 441, where the author states that this system is exceptionally useful where two existing cables can be used in parallel on one split-conductor switch. I am not of this opinion, since although a certain economy in switchgear is possible by adopting this system, it involves the waste of an entire cable. The characteristic of the split-conductor system is that when one of the systems breaks down it cuts off both. Now the great value of having duplicate transmitting equipment is just that one unit is left to carry the current when the other fails. In such a case the parallel-feeder system offers more advantages. In the first place it only cuts out the faulty feeder; secondly, it may be endowed with a bias, and hence it may possess the advantages as regards sensitiveness and stability that have been referred to above; and, thirdly, the protective gear and the switchgear are very little more elaborate than those required for a single split-conductor equipment. Hence there is no question in my mind that the split-conductor system should not be used where two fully-insulated cables are available. The only case in which it can be considered competitive is when there are two paths for the current provided which are insufficiently insulated from each other to withstand the full working voltage, such as is the case in the specially designed split-conductor cables.

Mr. F. Forrest: It is now the standard practice in large generating stations, both in this country, and abroad, to provide duplicate pumps and auxiliaries in connection with the main units, although it will be generally conceded that such things as circulating water pumps are among the most reliable pieces of apparatus in the station. It therefore does not seem logical to install single main switches for the alternators, as shown by the author in Fig. 20, especially as these switches are complicated pieces of mechanism and are likely to be subjected to very severe stresses. I suggest that the duplication of the main oil switches is essential in large generating stations. It is not always the case that a big switch is out of service due to an internal explosion, or due to its failure to break on heavy short-circuit, but as often as not such a switch fails due to some minor defect in connection with the switch-operating circuits, or to the operating mechanism. Such defects cannot always be located and rectified immediately, and until they are rectified the main turbo-alternator is compulsorily out of service. The author's argument that one good circuit breaker is better than two of inferior quality is sound, but I think that he will admit that one good circuit breaker is not so good as two good circuit breakers. One of the problems which supply undertakings have constantly to solve, is how best to protect the oil switches which were installed in the generating stations years ago, and which were then of ample breaking capacity, but which are now, owing to the increased plant, no longer able to break satisfactorily the increased short-circuit current. The most satisfactory method is to install current-limiting reactances in series with these switches, either by subdividing the busbars by busbar reactances or by installing sub-busbars to which such switches are connected, and to place reactances between the sub-busbars and the main busbars. So much trouble

has been experienced due to the fracturing of the porcelain switch insulators that users have been seeking another form of insulator which will have a certain degree of elasticity. Bakelite is being extensively used for this purpose, and so far is proving very satisfactory. Where porcelain must be used an internal bush of micanite or other insulating material should be employed, so that the circuit is not earthed if the porcelain breaks or cracks. The failures of oil switches may be divided into two classes:—(A) Those which occur before the switch commences to operate, and (B) those which occur while the switch is operating. In (A) we have breakages of insulators due to stresses set up by the passage of heavy currents. The repulsion of the moving main or arcing contact is due to the same reason, and because of their incorrect shape, whilst in (B) are included internal explosions due to the explosion in the oil tank caused by the arc firing the gas under pressure. The author, who is responsible for the design of switchgear which is probably unequalled anywhere, has paid very great attention to these possibilities, but I am surprised that he has not dealt more fully with the necessity of giving all oil switches the highest possible velocity at the point of break. In Birmingham we specify a velocity of 5 ft. per sec. at the point where the sparking contacts are separated, and we are able to obtain, from most of the leading manufacturers, switches capable of breaking with this rapidity. I believe that this velocity could be still further increased with advantage, and I should be glad to have the author's views on this important point.

Mr. Christopher Jones: The author has for long advocated the consistent enclosure of all conductors and insulators, including a continuous earthed metal core throughout the whole supply system, from the generators to the load, and even to lighting fittings, and with these views I fully concur. He refers on page 426 to the earth circuit to the metal cover of all portable plant and appliances being continued through an earth conductor in the flexible cables. The recommendation to surround the outer insulation of the flexible cable, i.e. trailing cable with an earthed sheath of copper braiding in addition to the compulsory earth conductor, thus continuing the metal cover over flexible cables also, is a good one. I have gone carefully into this question in connection with a large number of electrical coal cutters under my charge and I am replacing the ordinary 4-core C.T.S. cable with the class of cable referred to in the paper. On page 426 the author, in dealing with alternators, etc., refers to the entire framework being earthed to avoid the risk of shock to attendants, and states that more often than not the proper finishing off to the metal enclosure has been neglected at a most critical place, namely at the terminal ends of the stator windings. I have quite recently had to condemn such methods in connection with a 1 500-kW turbo-alternator where 3 000-volt rubber tails were in view and accessible, with the weakness pointed out by the author. The plant was supplied to comply with the Home Office Mining Regulations, but it does not under the above conditions. The question of the standardization of terminal cable-sealing boxes has been mentioned, and very rightly so. Mining electrical engineers are alive to this and have been so for the past 10 years. It is high time that manufacturers supplied such equipment as a standard for works and collieries. Ninety-nine per cent of makers of electrical motors are not alive to the requirements of Mining and Factory Regulations. Apart from the fact that the regulations call for such practice it is in the interests of safety to install plant that is electrically and mechanically efficient. Quite recently I had occasion to purchase single-phase, 440-volt motors. These were supplied with an ordinary large tumbler switch fixed to the motor case, the cover of which was not earthed, although the motors were required to be placed in a damp butcher's warehouse. The manufacturer's branch office were informed that the switch on the motor did not comply with the Factory Regulations and that they must supply the proper article. As no notice was taken of this I wrote pointing out the seriousness of supplying apparatus in this manner. The reply was to the effect that it was an oversight at the works and that I was to return the machines. I was told later, however, that the firm had sent out thousands of motors in this manner and that I was the first to complain. The author refers to the less attention and maintenance required for ironclad gear, apart from the saving in initial outlay for housing. This housing question has been overlooked in the past when switchgear costs were under consideration. For rural supply districts with small substations, the capital outlay on houses or substation buildings has to be seriously considered. I have had leakage protective devices installed on all low-tension feeders for the past 12 years, and these have proved to be highly satisfactory. At a recent meeting of the Electrical Power Engineers Association, when the subject of electric supply in Hong Kong was being discussed, special reference was made to the amount of trouble obtained with open-type gear, and it was held that the only solution would be the solid type of gear mentioned in the paper. Reference is also made in the paper to indicating and interlocking devices being conspicuously labelled, and to the advisability of coloured lamps being used. In a high-tension cubicle of the non-draw-out type recently delivered the lamps were so arranged that to replace broken or defective bulbs the alternator would have to be shut down, as the attendant had to reach across bare high-tension busbars. The system shown in Fig. 26 is to be commended. The earthing arrangement shown in Fig. 25 is also a very desirable feature, from the point of view of safety. A d.c. 550-volt switchboard which I had occasion to inspect for a colliery was supposed to comply with all the Home Office Regulations, but I was surprised to find open-type bare busbars placed on top of the board, which was in a power house where an overhead travelling crane was used. The circuit breaker and isolating link handles were not earthed, nor were the metal covers of meters.

[**Dr. C. C. Garrard** also took part in the discussion at Birmingham. The substance of his remarks will be found on page 447 in connection with the discussion before the Institution.]

Mr. A. M. Taylor (*communicated*): With regard to

the separation of phases referred to on page 430, while agreeing in the main with the author's remark that "should an internal fault occur, the arc cannot be long or sustained," and the deductions which follow, I think that this ought to be qualified by some statement as to the limitations of the power passing through. It would appear that, although perhaps no serious "burn-throughs" have been obtained up to the present between any of the conductors and bends leading into the Reyrolle type of switch, it is largely a matter of the power going through the circuit before the outer metal sheathing will be burst through with a sufficiently large hole to permit of the arc repelling itself into the surrounding space. I know of a case where single-phase voltage, backed up by only a trifling kVA capacity, burnt large holes in a paper-insulated cable in which the lead sheathing was 3 inches in diameter. In another case a large hole had been burnt in a three-core cable of some 3½ in. diameter, although the arc was smothered by being buried in the street. In the latter case it is true that there was 10 000 kVA of capacity behind the arc. What would have been the result had 50 000 kVA been behind the arc, and if there had been no surrounding earth to quench the flame? This latter case would correspond somewhat to the bends and hoods of the metal-enclosed parts of the switchgear. Subject, however, to this qualification, I believe that the author's remarks as to the advantage of enclosing each phase with a continuous metal sheathing are perfectly correct. Where it is possible for an arc to get long enough and open enough (as possibly in the case cited by the author) for sufficient resistance to be incorporated to keep the current below the operating point at which the relays are set, there would appear to be great difficulty in preventing a disaster such as that mentioned on page 430. Referring to the author's statement on page 426 that "carried to a logical conclusion, overhead lines would be replaced by underground cables," I agree that this is the ideal case, but, as he says, the cost is excessive. Two years ago I advocated a wholly underground system operating at 150 000 volts,* but I found that engineers' minds were so obsessed by the tremendous difference in cost between overhead lines and underground lines that for long transmission they condemned underground schemes offhand, being unaware that if underground transmission could be carried out in sufficient "blocks" of power, at the voltages which I proposed, and if the cables could be laid alongside the railways, there would not be so much difference between the costs of underground and overhead transmission. However, the next best thing to running the trunk transmission lines entirely underground is to run underground those parts that are in the towns, or that approach the switching stations, and to change from bare conductors to lead-covered cable at a height of not less than, say, 30 ft. above ground (i.e. on the mast itself) and to have no bare conductors entering switching buildings. This is what I am now recommending. By such arrangements the awful catastrophe by which seven men in America were burnt to death in doing switching work on the Niagara lines would be avoided—not to mention the very serious dislocation of supply which this must have entailed. The author gives on page 446 as one of the requisites for safety and continuity: "A stable neutral point at earth potential," and again he says on page 439: "Rather save . . . by connecting the neutral direct to earth." Although it is true that in America there are many installations in which, on the high-tension side of the step-up transformers, the neutral is earthed directly, I believe that, at any rate on 33 000-volt systems in this country, and with underground cables, it will not be advisable to do this. I have recently made careful investigations into the possibilities of resonance being set up in such circuits by the "triple harmonics" (left unsuppressed in spite of the delta winding of the primary) set up by the transformers themselves, where single-phase transformers are used, and I was surprised to find the exceedingly valuable damping-out effect performed by the earthing resistance. Without this, resonance effects would, on a 10 000-kVA transmission system at 33 000 volts, become quite serious when the total length of cable became much over 20 miles, and as on some big systems there are sometimes two cables in parallel (giving 20 miles of cable over a 10-mile route), I think it would be a great mistake to cut out the resistance entirely from the earthing connection. At the same time, in the particular case which I investigated, the earthing resistance was so very much higher than sufficient merely to check resonance that possibly sufficient "stability" could be provided to meet the author's suggestions substantially, without inviting the introduction of triple-frequency resonance where at present none exists. It is a matter of the careful investigation of each individual circuit and of its group of transformers, i.e. each circuit must be dealt with on its merits. (I may add that the investigation is rather involved and should not be undertaken by a tyro.) Of course these remarks will not apply to the earthing of the generating system—at any rate not to the same extent—though even here it may be inadvisable to cut out all the resistance.

* *Journal I.E.E.*, 1923, vol. 61, p. 220.

The Author's Reply to the Discussions Before the Institution and at Birmingham and Manchester.

Mr. H. W. Clothier (*in reply*): I have noted as a trend in the discussion that there is an apprehension of failure in details, which seems to promote the idea that in a power station or substation one must be able to "get at" this or that part of the apparatus. I must say that on the other hand I look to the time, arising out of the haze and endeavour of the last 30 years, when operators will no longer need to be on the constant qui vive. We shall dispose of our troubles with bad insulation, with fittings which come loose, with relays which trip when they should not, and with the hundred and one other things which have gone wrong, by the

simple and common-sense process of learning from past experience how to design in a way which will avoid defects in every minute detail. These little annoyances, trifling in themselves but far-reaching in their effect, should not in future pester and endanger that broader expansion in the utilization of electric service which should be our future aim in this country. Many of these details may be overcome by using conductors and insulators buried in compound or oil; in which case they need be no more accessible than the conductors and insulation of a well-conducted cable laid solid in the ground. I can imagine how busy those people would be who are always wanting to look at the joints on their conductors and the surfaces of their insulators, if their methods for switchgear had been allowed for transmission, and bare conductors had been laid in ducts in the ground or mounted on walls, just as they nowadays want to fix the busbars in their power stations. And yet, as I look at the issue, there is no more reason for having access to the busbars and connections thereto than to the main conductors. In fact, perfection of busbars is easier to attain, as this covers only a small part of the system, whereas any improvement of the cables must spread over the whole network. I admit that there is still room for research in the improvement of insulation and I agree that insulation failures, on certain classes of apparatus and with certain materials, may be a heavy charge on the installation. Until such research as may be possible in the future brings the art of insulation to a state of scientific perfection, my appeal is to carry a safe margin. My experience, as recorded in the paper, is that a reasonable factor of safety, such as is common in engineering construction, will give protection from insulation failure, provided that the materials are suitably preserved and kept out of the reach of any intruding foreign matter. With our present knowledge of insulators, and with a good safety factor, the industry can obtain security now, although I admit that after more extensive research it may be attained more economically. But, notwithstanding the possibilities of research, the preservation of insulation in oils and compounds, on which much experience is now available, cannot be disregarded. After all, one of the dangers is the poor and unreliable insulation provided by air, and this, I fear, no amount of research will cure.

On account of insulation failures, Mr. Wedmore has a leaning towards the duplication of circuit breakers. What one has to guard against is the interruption of supply due to such failures. I suggest that to have two circuit breakers instead of one does not reduce the risk of such failure. On the contrary, this risk is increased, as there must be more insulators, the failure of any one of which in service may result in a busbar fault. If the anticipation of failure of insulators and switches is really the controlling factor of the switchgear layout, then the best policy is to cut down the number of them and utilize the consequent saving in cost to improve the quality of those which remain. Mr. Wedmore says that duplication carries with it " simplicity of the whole scheme and its operations." Multiplicity does not generally lead to simplicity, nor does it in the case of switchgear. It may be simpler to use two oil circuit breakers to change over from one busbar to another than to draw out a circuit breaker and change over the plugs, but with all circuit breakers it is necessary to provide isolation on both sides; and so if the isolating switches also are operated there are actually more operations in changing over with duplicate circuit breakers than with a single circuit breaker and ordinary selector switches. To secure efficiency of operation by duplication, the circuit breakers should be of the draw-out type. If the advantage of the draw-out type is admitted, then the consideration arises that on the single-circuit-breaker-per-panel type of gear one spare circuit breaker in each station will serve all the purposes of duplication. It would seem that duplication is, after all, only justified as a means of substitution for a broken-down part, in which case certainly one good circuit breaker is better than two made for the same total cost, because it must reduce the risk of this part needing substitution. A failure of the circuit breaker means a shut-down of the station, or at least a section of it. In such an event the breaker can be withdrawn and replaced in a few minutes without a flurried series of operations. A failure on the connections to the breaker from the busbar also means a shut-down, and it is as likely as not to be on a conductor, which prevents the particular circuit from being put into commission immediately whether there is duplication or not.

Several speakers have referred to American practice. It does not follow that what suits American control is necessarily the right example for this country, but in connection with circuit breakers it is opportune to note from a recent Report of the American Institute that the manufacturers of oil circuit breakers are making " herculean efforts " to secure satisfactory oil circuit breakers of sufficient interrupting capacity. The elimination of the isolating-switch troubles is also being sought after. This is evident from the same Report, which continues: " in one of the newest large central stations practically no disconnecting switches are used for disconnecting the oil circuit breakers from the bus or line. The disconnection of the breakers is accomplished by lowering them below their normal position, thus breaking the connections and isolating the breakers." This practice in America is also confirmed by Mr. Davies, who states that it is perhaps the best feature of metal-clad gear.

Whilst American stations are in general larger than anything attempted yet in this country, the system of distribution by feeders starred out is possibly no more searching on the switchgear than such systems as that of the North-East Coast where many power stations having an aggregate of 300 000 kW are all linked together in one mesh of ring mains, separated only into sections after the occurrence of a serious fault. It is on this large testing ground for bringing out the weak points that the principles described in the paper have been tried out. So although agreeing, as Mr. Wedmore wisely says, that there is no finality in design, at the same time it would be an indictment of lost opportunity if something very definite and useful did not come out of the experience, something which, to say the least, will bear its mark on future practice in this country, if not in other countries also.

Several speakers have also referred to the duplication

of busbars in a way which seems to point to a misreading of the paper. Two reasons justifying the retention of duplicate busbars on switchgear in important situations, such as power stations and large distributing centres, are recorded on page 428. Maybe this misunderstanding has been brought about by the discussion of the process of changing over from one busbar to another, which is another subject. Notwithstanding Mr. Ferguson's objection, I feel that the consensus of opinion is in favour of disconnecting any circuit from the busbar before changing over from one busbar to another. Other contributors confirm that, when dealing with large amounts of power, it is not safe to attempt the rapid juggling of circuits. Nor is it at all necessary on a system that has been laid out to maintain continuity to all consumers. To effect this object any circuit may be opened at any time, as happens automatically on the occurrence of faults, without causing cessation of supply through alternative circuits.

Another general subject on which there appears on the part of some speakers to be a misreading, is the breaking capacity of circuit breakers and the interpretation of B.E.S.A. recommendations. Mr. Wedmore says that it is of very little use to split hairs on "small margins on supposed factors of safety now current." We are in sight of "formulæ established on scientific principles." The prospects of "revolutionizing designs" must be waited for with intense respect from such an authoritative statement. As one who has taken a part in helping to bring about the tests and in the supply of material for investigation, I am not permitted to discuss the outcome, but until the tests have been carried out upon a much larger scale (that is, with larger power behind the short-circuit) I cannot think that the discoveries up to the present justify the brushing aside of such vital questions as factors of safety which practical demonstrations under service conditions (often failures) have evolved in certain established designs. These are not to be shaken by merely the promises of formulæ to come.

Mr. Ratcliff draws attention to the elastic nature of statements about breaking-capacity ratings; and this, coming as the declared opinion of a large user, notwithstanding the existence for two years of the British Standard Specification, indicates a state of affairs which calls for some explanation.

Dr. Garrard fears that my approach to the subject will harm British reputation. British reputation is not made by the B.E.S.A. but by the results of the work produced under the direction of their recommendations. Dr. Garrard says that the breaking capacity of the switch must generally be in "inverse ratio to the reputation of the maker." Surely, if that be so, it is in the interest of the whole country to declare a better standard. Anyhow it should be definite. If it is to be what is known as the B.E.S.A. rating (six times the aggregate kVA), then a factor of safety of at least 200 per cent is required. If it is taken at 10 times, a factor of safety of 100 per cent is better. These safety factors would meet the worst conditions illustrated in Fig. 19. Dr. Garrard goes so far as to admit that it may be necessary to specify the power factor. It is only a step further also to state the factor of safety which is to be the objective in the design.

In the attention given to switchgear construction the discussion on protective systems has taken a secondary place. I think it has been generally admitted that a better standard of stability is required, and that on the whole it is not working in the right direction to cut down the amounts of fault-current settings. Even the sensitive systems of generator protection which once were given to operate on fault currents of 7·5 per cent of full load are admitted to be more reliable if raised to 15 per cent of full load. On feeder protective systems the working of current transformers over the point of saturation is likely to introduce difficulties in the standardization of a common design of current transformer for all purposes, including feeders with tees as shown in Fig. 28 (single switch substation). The multi-airgap current transformer having a straight-line characteristic up to 10 000 amperes, on the other hand, has prospects as a standard which will suit most conditions and situations that arise in general transmission practice.

As to voltage-surge arresters for protection against lightning and atmospheric voltage disturbances, Mr. Rosling points out that whilst insulation may stand momentary stresses, each instance may by cumulative action tend to an ultimate localized puncture, and Colonel Edgcumbe seems to confirm the opinion that it is unfair to the cable to expect it to perform a function which should be part of the switchgear's duty. The practical difficulty is to find any surge-arresting device which is capable of reducing the excess stress by any really effective proportion. The large shunting action of the cable itself is the reason for this. For adequate protection any artificial discharge resistance would have to be of such a low value that serious trouble would be experienced, in view of the heavy power current which would follow through it. The suggestion has been made that there would be undue stress at the point of juncture between the overhead line and the cable. Of course at this situation all sharp corners and small clearances must be avoided, but from the theoretical consideration of this subject the cable acts as a shunted condenser, in which case, although the voltage stresses are admittedly greater at one end than at the other, no voltage-reflection effect takes place at the point of juncture but, in fact, an actual tapering down of the surge voltage immediately commences due to the flattening effect of capacitance of the initial portion of the cable. There is no abrupt voltage-wave distortion at this point, the cable acting as an ideal condenser for this purpose. In addition to the tapered flattening effect, a cable will have, due to sheath and dielectric losses, a heavy dissipative effect on the energy of the surge. The necessary precautions are, first, to use an appropriate length of cable in order to provide sufficient capacitative shunting action, and also to ensure that any surge passes through an appreciable length of heavily damped circuit in order to prevent severe voltage reflections occurring between the line and the inductance of the plant—in most cases a length of 200 yards or so is adequate. Secondly, to ensure a sufficient safety factor in the insulation, in the cable and inside and outside the dividing box. This safety factor is in any case necessary to withstand surges which occur in normal system operations. In this connection the

duration of the atmospheric disturbance when severe stresses do occur is extremely short, whereas the stresses occasioned by normal system operations, while appreciably lower, have longer duration. To have a large cable network and to earth the neutral point through a sufficiently low resistance are the most efficient safeguards against internal voltage stresses. There may be some combination of circumstances where, as cited by Colonel Edgcumbe, an apparent improvement has been secured, but, in general, artificial surge protective apparatus can only make a small proportional reduction in the stress, whereas, on the other hand, they may themselves set up cumulative oscillations which annul any advantages to be derived from them. To avoid this, if any apparatus is used it should be of a series damping nature of the Campos, Thornton, or Grant type, rather than of a discharge nature like the horn gap, or similar device which permits a sustained discharge through a resistance. The problem of arresters, buffer charging resistances for transformers, and similar examples of extraneous apparatus which sometimes find a place, cannot be finally disposed of by this discussion, but the tenor of the discussion leads me to suggest that with a little more attention to the subject the use of them may be abandoned eventually. Such devices do not always enter the lists when the need comes for action, and on that consideration alone the true safeguard is to make plant capable of withstanding short-circuits and an adequate pressure test without risk of incipient injury or flash-over; it should then be independent of those protective devices of doubtful efficiency.

Dr. Garrard's proposal to improve cell-type switchgear by making it vermin proof, and to cover the busbars and connections with mica insulation, is certainly a step in the direction of the more complete enclosure obtained by the all metal-clad gear, but the switch houses of large power stations with cell gear, such as Hell Gate in America which he has cited as an example, have become so unwieldy as compared with the metal-clad form that it is questionable whether the practice will survive unless, indeed, Dr. Garrard can make his insulation covering so complete as to allow great reduction in the space now occupied. It is opportune here to note the comments of Mr. Gregory on this subject. Notwithstanding the extra space entailed by the duplication of circuit breakers, the recently published experiences at Calumet (also of the cell type with separation of phases in isolated parts of the building) go to show that, despite the large dimensions and apparently elaborate precautions for isolation, it is still possible for the effects of faults to spread over panels on several circuits and even from one phase building to another.

It has been stated in the discusssion that the effects of a breakdown on cell gear are more readily repaired than upon metal-clad gear. This depends, of course, upon the extent of the damage, but in any case what matters most is the time taken to get the supply restored after a breakdown. Much of the time is frequently taken in getting the maintenance engineer to the spot, which is the same in both cases. Where time is saved is in clearing away the results of the breakdown, and in the cell gear this almost invariably extends to adjacent panels which, if not actually distorted or burnt, have to be cleaned and overhauled. On the other hand the metal-clad damage is confined to one unit; and the insulators and conductors of the others, thanks to the invulnerable enclosure, remain intact and ready for continued service. Indeed, in some cases which would put the counterpart in cell gear out of service, the supply would not be interrupted at all through the metal-clad gear.

Having now dealt in a general way with the main criticisms it remains to reply to detail comments and questions.

Mr. Wedmore says that a modern motor-car or flying machine would not have been built 20 years ago, but he asks why should not the protective gear of the present day have been manufactured 20 years ago? I think it was. It was at that time that the balanced systems of protection were developed on the North-East Coast, and metal-clad designs were made only a year or so later. At that time the necessity had been realized, at least in that part of the country. The single pilot in the middle of the cable is no doubt attractive, but I fear that it would require another revolution of the balanced systems. At present the single-wire pilot would be subject to interference by induced currents, and, moreover, it has never been accepted as good practice to enclose the protecting pilot in one cable with the main conductors, because a fault on the cable might bring the high-tension voltage on to the low-tension relay system. If the pilot were used as a high-tension connection, which its insulation might justify, there would need to be a potential transformer at the ends. Potential transformers on protective gear have up to now been tabooed. The Kuyser system of generator protection has not progressed, I think, mainly on this account.

Dr. Garrard agrees with me that some form of standardization of terms is required in order to express the stability of protective gear. Mr. Leeson's comments on this subject will need to be taken into consideration. A good margin between the test-room results, or promises of performance, and the "service setting" is necessary to ensure stability under service conditions which cannot be reproduced artificially, and hence my preference for raising the fault settings. Some form of proving house also is an urgent need. The proving should include a record on the maximum "through" current possible without inadvertent operation. It is not yet clear that there are no unbalancing influences within the biased relays, or that the unbalancing in the primary circuits —for instance, during arcing earths—will not give an unexpected instability in the system of feeder protection mentioned by Dr. Garrard. This may account for the comparatively slow development of this system. The diverter relay, on the other hand, acts as a person would if given sufficient time; that is, at a stage in the magnitude of the "through" current it resets, as it were, the tripping relay, giving it greater stability. Its correctness is not dependent upon a balance between the restraining and operation currents on two different iron cores of the relays, which is additional to the balance required between the cores of two different current transformers.

Dr. Garrard's two incidents of injury to men appear to indicate some imperfect construction of interlocking

devices. To my mind the argument points to the need, not to dispense with interlocks, but to improve them.

As to internal losses in the lead-covered reactance coils, it is the practice to divide the lead sheathing into sections each of which is separately earthed. So the losses are practically resolved into I^2R losses, and owing to the smaller sections of copper which are used on the open type these losses are less on the cable type. The following is one comparison recently made in connection with an actual specification :—

33 000-volt 11 per cent 220 kVA rated reactor :—
Open type, 11 kW approx. at full load
Metal-clad type, 8·5 kW approx. at full load.

These figures are based on commercial ratings as obtained from manufacturers, and a truer comparison may be necessary by considering to what extent the copper section of the open-type reactance could be increased on the cost basis.

The "through" rating of a circuit breaker is not exactly the same as its breaking capacity. The circuit breaker should be capable of carrying the maximum current that can pass through it for a longer period than that when normally operating at its maximum breaking-capacity rating. As Mr. Ferguson suggests, the time for "through" ratings should be stated at 1 second and 5 seconds if the American practice is to be taken as a guide.

Dr. Garrard would not rely upon something which he cannot see. He fears that a closed oil switch might not be making contact. The object in the closing of the earth circuit within an oil switch is to make the earth contact in safety to the person actually making the earth. It is not to be supposed that a man would be expected to touch a cable outside before ensuring that the cable is dead by driving a pick through it or by some other such precaution.

Mr. Lovell also refers to this earthing device and suggests that it might cause a three-phase fault which might not operate the protective gear. The practice is to earth one phase at a time, in which case the amount of fault current would be limited by the resistance between the location and the neutral point.

I note the objection to the proposed vibration test on relays and agree that some more perfect example of the "jerks or shocks" to which a relay may be subjected on a switchboard is necessary. Some form of accepted standard device is required, which again would be an instrument to be used by some future Proving House. I think the complication of devices on protective systems is not due to voltage balance any more than it would under similar conditions be due to current balance. In fact the pilot-wire voltage may be higher with current balancing on long lines by reason of the voltage-drop. I question the utility of circuit breakers of 750 000 kVA breaking capacity with the "biggest possible plant," even with a liberal use of reactances, but I think that their use will depend upon the power factor at which the rating is fixed. Circuit breakers of 1 500 000 kVA rating are specified in this country where the aggregate plant is 150 000 to 200 000 kVA. In stations in the future of 600 000 kVA which are spoken of, I think Dr. Garrard's limit is likely to be on the small side.

Mr. Christianson's comments on interlocking also suggest to me that better attention should be given to this subject in the future. With the railway system of interlocking, would one countenance the temporary putting out of action of important interlocks, thereby endangering life ? I think not ; and switchgear, to be perfect, should be no less safe. He seems to hover between open cell gear (" cubicle " type) and the metal-clad, preferring, if breakdown occurs, to repair the former. He must humour the old love whilst he takes the new love home. I agree with Mr. Christianson that complete enclosure or inaccessibility is also essential on low-tension switchgear, and that the question about the design of change-over is a matter for operating engineers. In due course these subjects will settle themselves by force of general practice. It is as well that simple plans be adopted, because, contrary to Mr. Christianson's expectations, I do not find the engineers very willing to pay for the special arrangements sometimes called for by peculiar idiosyncrasies in demands. I agree that the rapid change-over features are more costly to produce, and in view of the risks involved it is to be expected that the course of events will follow the lines which are the most economical. If the rapid change-over must be made I agree with Mr. Christianson in his choice of the two-oil-circuit-breaker method. It is liberal of him to make this choice despite his own design with front plugs and the earthing features embodied therein. There is no need to separate the busbars more than shown in Fig. 10, as these are compound filled and the metal-clad enclosure is to all intents and purposes invulnerable. Therefore busbars may be close together like armoured cables on racks.

Among many other interesting statements, Mr. Christianson asks for my views on the commercial and technical feasibility of employing viscous oil for busbar chambers. I think it may be necessary to resort to oil filling for some conditions of high current values and high voltage, but compound has certain advantages which would always claim from me a preference.

I am of the opinion that notwithstanding the addition of the extra coil on the relay similar to that adopted for overload and leakage relays, there are risks in attempting settings as low as 7·5 per cent of the generator full-load current. I do not consider the risk to be worth the gain of covering a little more of the alternator winding, which, being near the earthed neutral, should never be in danger of breakdown to earth provided there is sound insulation between turns and reasonably low earthing resistances are used. The system using a coil between the starred point of the relays and a common starred point of the transformers may not be altogether free from unbalancing influences due to external phase faults, and the earth coil will be liable to operate only to a slightly less degree than the phase coils. In this connection Mr. Ross, I think, agrees with me in preferring 15 per cent with the sensitive leakage coil. With diverter relays 10 per cent gives equivalent stability.

I think that Mr. Trencham is begging the question a little when he says that the very first oil circuit breakers used in heavy power stations were of the explosion-pot type. The explosion-pot type, as the term is now understood, is that invented by Mr. Hilliard and advocated by

Mr. Bernard Price, which consists of extra pots surrounding the contacts and contained within another oil chamber in the form of the ordinary switch tank. The first large power station in this country to use oil circuit breakers was Deptford, and the second was Bankside and in these cases the pots were of glass and porcelain respectively. The well-known American General Electric switches were a later introduction, and they have undoubtedly given excellent service on cell-type switchgear. The object of this type is to retain the oil within the pot, but in the type referred to in the paper the pots are used to generate a pressure within, which assists to expel the plunger at a high velocity through a clearing hole at the bottom. I admit that the arc is started within the pots in both cases, but in other respects it seems to me that in construction and principle of action the two methods are separable in classification. I agree with Mr. Trencham that additional variables must not be introduced into the standard rating of circuit breakers. My whole desire is to have a standard based upon invariable quantities that will be understood. This is not a confusion with selection but a fundamental matter of measurement.

The points of Mr. Ferguson's valuable contribution are of three kinds: he agrees, he disagrees, and he misinterprets. He agrees with all the main principles; in fact, his entry into the production of metal-clad switchgear during the last few years has contributed not a little to the present prominence of the metal-clad principle. The points in which he disagrees relate chiefly to constructional details. These include compound-filled transformer enclosures and busbar change-over plugs. His innovation just put into use includes the immersion of these parts in oil, a practice which in one form or another has been applied for several years. One design embodying both these features is actually shown in the paper (Figs. 7 and 25), but there must be discrimination in such details, and in the majority of cases for ordinary service the simpler forms shown in Figs. 4 and 8 adequately meet the requirements. As a general rule compound filling is to be preferred; it dispenses with the possibilities of oil leakage, and the explosion and fire risks are less; moreover, the compound gives a support to busbars and other conductors, helping them to withstand the large stresses on "through" short-circuits referred to by Mr. Ferguson. He expects, in the event of a busbar breakdown, to change over automatically from one busbar to another in 0·8 second by the use of duplicate oil-switch movements. I think it would be a surprising achievement in a large power station (and even without a "separate coupler" to parallel the busbars first) to change over the generators and the load in this time. I suggest that operating engineers in the power station and switch house would not view this project with equanimity. I think they would be happier to know that the effort was being directed towards so making the switchgear that busbar faults do not happen necessitating this rapid change-over.

The general objection to duplication of oil switches which is discussed above, applies here also with the added disadvantage in Mr. Ferguson's arrangement that the connections from both busbars are brought down into one common circuit-breaking chamber. The dangers of this method are also discussed by Mr. Davies and Mr. Mold, with both of whom I agree on this point. Other contributors to the discussion on this question have referred to serious accidents in changing over and seem to confirm the opinion expressed in the paper that, for ordinary service, it is preferable to rack out the circuit breakers and incidentally to make sure that there are no hasty operations in effecting a change-over. The alternative is to have entirely separate circuit breakers. The question is: does the need justify the expense? I suggest that the consensus of opinion is to be found in Mr. Davies's statement that 90 per cent of the supply undertakings would accept the simple plan which, in Mr. Ferguson's judgment, is the "crudest method imaginable." Mr. Ferguson refers to a statement of an operating engineer at Stepney and a discussion at Sheffield. The fact is that in both these places the arrangement (Fig. 8) has been in use for about 15 years and all extensions, including recent ones, have contained the same principle. It is strange that the first intimation of any dissatisfaction should come to me from Mr. Ferguson. True, as also emphasized by other speakers, including Mr. Townley, the operating engineers' experiences must have first consideration. The need for efficiency includes the reduction of the number of operations to a minimum, and that would seem to be an explanation of the existence and development on a very large scale of the simpler plan. If the change-over had to be frequently made, the alternative of duplicate oil switches would be more necessary, but in most places where the layout permits of opening any circuit as required, the spare busbar on metal-clad gear is rarely, if ever, used. Certainly in the case of Sheffield the spare busbar has only been used twice since 1913—both times for extension purposes. It has been frequently demonstrated that a circuit can be changed over in less than 3 minutes, which is the routine period at Sheffield to wait before reclosing a breaker after opening on a fault. The idea of needing rapid change-over devices is a relic of the days before alternators were run in synchronism. As to Fig. 28, the fuse is suitable protection for the transformer if properly enclosed. In the event of the fuse failing and itself developing into a fault upon the link, it is cleared by the action of discriminating protection and the circuit breakers at both ends of the line.

Among the items which have been misread, Mr. Ferguson, in common with other speakers, takes the paper to infer that duplicate busbars should be dispensed with in a central station scheme. The paper shows duplicate busbars in all such cases and even gives two reasons (items 1 and 2, page 428) for their retention on metal-clad gear. The main inference in respect to busbars is that it is necessary to remove the risks attending the change-over from one busbar to another and that, by suitable layout of equipment and safety factor in design, the need for the frequent trial of this risky operation can be eliminated. They are seldom included in general practice on substations, which is in favour of the simpler sectioning of busbars. Mr. Ferguson also appears to read into my paper a proposal to cut out the use of reactances altogether, whereas the paper merely draws

attention to the necessity of exercising care in determining the values and location of reactances. Moreover, the paper does not propose to neglect to take external reactance " into account in calculating the short-circuit current."

The suggestion in selecting the rating of circuit breakers is not the method which obtained 10 to 12 years ago. The rating as defined at present is accepted, but with the addition of a standard of quantity which at present is missing in regard to both power factor and factor of safety. Stability of the neutral point is best secured by " dead earthing " the neutral, but this is only recommended in the paper as being preferable to using a resistance which is too small. The compromise is, as recommended in the paper, an earthing resistance which will allow twice the full-load current of the generating plant to pass through it. The forces given as the loading of busbars at the peak of the short-circuit current appear to be high, but in the absence of a standard understanding as to the meaning of the size of plant corresponding to a 750 000 kVA breaker, it is difficult to check Mr. Ferguson's figures. If the circuit breakers are rated on B.E.S.A. recommendations, the plant would have an aggregate capacity of one-sixth; that is, it would be 125 000 kVA with 10 per cent internal reactance, or, say, 250 000 kVA with 10 per cent additional reactance. The corresponding short-circuit at the maximum of the transient would then be 2 500 000 kVA, and I suggest that in stations like this a 1 500 000-kVA circuit breaker would be more suitable. It is stated in the paper that a generator circuit with more inductance than 10 per cent internal reactance may require on short-circuit greater breaking capacity that that recommended in the same clause as a standard (page 434). Mr. Ferguson does not agree with this on the ground that an addition of 10 per cent external reactance will only alter the phase angle of the short-circuit current by about 3 degrees. This may be perfectly correct, and a difference of 3 degrees does not materially increase the arc energy, but there may be circumstances in the layout of reactance where the added external reactance amounts to very much more than 10 per cent, and it is in such cases that an adjustment in the switch rating would be necessary in order to compensate for the added arc energy due to very bad power factor, as there is evidence to show that beyond 85 degrees the arc energy increases very heavily. On the other hand the arc energy of a circuit of 45 degrees would appear to be about $33\frac{1}{3}$ per cent less. As recommended in the paper, it is of importance that the relationship between the arc energy and the power factor shall be accurately determined and taken into account when selecting the suitable rating of circuit breakers for their relative positions on the system, having regard to the natural and added artificial reactance in circuit. This, I think, also replies to Mr. Christianson's question, in which he says it is not clear to him that the plant output and reactance on short-circuit has anything to do with the ability of a given circuit breaker to rupture any stated power in kilovolt-amperes or kilowatts. The fact that it is not clear to Mr. Christianson shows that the full effects of artificial reactance require further elucidation by the collation and publication of research data on the subject. In one experience the addition of 30 per cent reactance to a short-circuit proved that a switch, which had a breaking capacity more than sufficient for the short-circuit without the reactance, showed distinct signs of distress on the same circuit with added reactance, although the current was proportionately reduced.

It is gratifying to find that Mr. Ratcliff is in the main in agreement with the views expressed in the paper. His experience on a high-voltage cable system is unique and of extreme importance to the art of protection. I think that his explanation of the use of reactances, not so much for permitting the use of switches having smaller breaking capacities as for preventing enormous concentration of energy, is particularly apt. I am sorry, however, that his experience with cables leads him to prefer the open type of reactance. Possibly this is a correct view for reactances on 33 000-volt systems at the present time, but when cables at this voltage have the same standard of reliability as 6 000–20 000-volt cables, then I hope he will revise his opinion. The metal-clad reactances are in use at the lower voltages and, as stated above in reply to Dr. Garrard, the losses need be no greater than with the open type.

The hazards of compound-filled busbar chambers are less than the counterpart of cellular gear, and the risks of short-circuits are correspondingly less, as there can be no interference with the insulation once the chambers have been filled in. On the other hand, if the remote possibility of a short-circuit did happen, the damage would be restricted to the particular chamber, whereas the experience with open-type conductors as recorded by other speakers is that the trouble almost invariably spreads from panel to panel, usually with disastrous results to the structure and causing extended discontinuity of supply. It must be remembered that the long arcs on short-circuits cannot be maintained on metal-clad gear owing to the comparatively close proximity of the conductors and earthed metal, and whilst there are many instances on record of serious explosions destroying switchgear buildings which have contained open-type switchgear, there are none known to have occurred to buildings enclosing metal-clad gear, nor is there any instance on record to my knowledge where injury has been done to adjacent panels. In the comparison of busbar design with cables it must be borne in mind that the clearances allowed in the case of the busbar permit a considerably larger margin of safety on insulation, and so there is every reason to expect that metal-clad busbars will be immune from breakdown. Hence, although busbar protection is by no means impossible, it has rarely been considered necessary.

I think it is hardly safe to depend upon the charging resistances in switches to protect the end turns of machine stator windings, as, although the charging resistance does reduce the heavy current transient on switching-in at or near zero voltage, it must be borne in mind that the abnormal stress may also occur at other times than on closing the stator circuit by its own switch. However, the consensus of opinion appears to be in agreement with Mr. Ratcliff, that charging resistances are desirable

in certain cases for machines on account of the moral effect of quietness in starting up. It is useful to record here that on the North-East Coast they are not used for switching-in static transformers, preference being given to suitable bracing of the transformer windings to enable them to withstand the heavy current transient stresses to which they are sometimes subjected. These stresses in any case are less than they must be capable of withstanding under "through" short-circuit conditions. Whilst the single-turn type of current transformer may be unreliable for protective gear of the balanced-current type, it is worthy of note that the converse is the case on voltage-balance systems of protection.

The point to note in regard to Mr. Ratcliff's remarks about discrimination by means of relays possessing different time characteristics in the diverter system is that the time difference is merely that obtained by reducing the inertia of a high-speed relay, the time difference of 0·05 second being all that is necessary, and being secured by speeding up the diverter relay to operate in 0·015 second. The operating mechanism of the switch acting under the smallest fault condition commences in 0·065 second, and still retains what has been called instantaneous action, which, though not strictly correct, is sufficiently so for practical purposes. It will be seen that there is a safety factor between the operation of these relays of 4 to 1, which is a security for stability.

I am glad to see that Mr. Ross supports my views on protective gear, particularly with respect to earthing-resistance values and the use of inertia to form, as it were, anti-surge relays. No trouble is experienced in balancing protective gear transformers when in their chambers, provided adequate clearances are allowed. I agree that it is desirable to open the field switch by means of the relay whether under fault condition or by hand, but the alternator manufacturers usually object to the latter as routine testing, on the ground that the rotor is unnecessarily stressed. Equivalent tests are obtained by means of the emergency switch or the relay after the turbine is tripped on the steam side.

Mr. Davies asks for a record of troubles in metal-clad gear. Most experience has been obtained in mechanical failures where the short-circuit kVA of the system has outgrown the original breaking capacity of the circuit breaker. In such cases faults have proved the necessity for stronger mechanical construction, which has led to the use of steel tanks and top plates securely bolted together. The failures through insulation are insignificant and have usually been traced to definite causes. The salient features are the localization of damage to the chamber in which the fault occurs. The suggestion that the horizontal break shown in Fig. 7 may be dangerous, in that the arc can be blown above the oil, is erroneous. The actual break takes place in the centre of the tank and under an ample head of oil (20 in.). The figure is diagrammatic and is perhaps misleading in this respect. Further, too great a head of oil may not be advantageous.

I agree with Mr. Davies as to the advantages of co-operation between supply undertakings and manufacturers. The only safe and sure way of arriving at a suitable short-circuit kVA-rating for a circuit breaker is from performances under actual service conditions, and I have always relied upon ratings obtained in this way in preference to purely theoretical considerations. As previously referred to, it is this experience with breaking-capacity performance that has led up to the comments and recommendations given in the paper for selecting a circuit breaker the performance of which will be perfectly satisfactory, both on the average and on the rare occasion. It is not always fully appreciated that British Standard Specifications refer to minimum values, and Fig. 10 was intended to show how only the easy case has been legislated for. I think that Mr. Davies is advocating a very dangerous policy if he relies upon any special design of movable contact to provide the necessary rigidity for the stationary contacts by forming a "lock" between their extremities. In the first place, I fail to see how this so-called "lock" is intended to be produced except in the form of a friction grip between the surfaces of the brushes and contact blocks. This merely constitutes a restraint, which can hardly be likened to a "lock." In any case, such a restraint will only be present during "through" short-circuits, and as it is equally important to make the stationary contacts immune from mechanical damage when the switch is opening under a short-circuit, I prefer to make these portions inherently strong enough to withstand the stresses to which they are subjected. In situations where insulation might be liable to possible surface damage by burning, certain advantages are offered by the use of a vitreous material such as porcelain. The risk of cracking during compound-filling can be eliminated if precautions are taken to prevent any appreciable difference in temperature between the two materials. I agree that a high-pressure test is not the best means of determining whether cracks are present, and I prefer to adopt alternative means. I presume that Mr. Davies refers to bakelized paper insulation, and this certainly has its own sphere of usefulness. One of its chief advantages lies in the control of the dielectric stress by means of condenser layers, and I have found its use in this way to be most effective, especially on the higher voltages. Although it is very easy to provide separate accommodation for potential transformers and fuses, the chief reason for not doing so is one of economics. I think that it is better to spend the money on the construction of a sounder and more robust potential transformer and embody it in the isolator chamber which is of liberal dimensions, as this makes for simplicity in the equipment. A further distinct advantage is that by using single-phase transformers, interconnection between phases is avoided, thus providing maximum security. Experience up to date does not record a single failure of a potential transformer mounted in enclosures as depicted in Fig. 7. This, I think, justifies the policy advocated and I have found it meets with general approval.

I note Mr. Hall's general agreement with metal-clad principles, but he apparently prefers the half-way measure excluding compound filling. I think that this is permissible in the smaller ratings and for low voltages, provided the clearances are suitably adjusted.

In reply to Mr. Bannister, I do not recognize any limitations for metal-clad gear for voltages above

35 000, but we are dependent upon the further development of high-voltage cable design and I do not anticipate that any difficulties will arise in providing satisfactory metal-clad designs for any voltage. I do not agree that air is necessarily a cheap form of insulation, as it has variable characteristics which entail large margins on the necessary clearances in order to cover the hazards which it introduces in comparison with solid dielectrics. With reference to phase-to-phase faults occurring in separated-phase types of construction, the possibility of simultaneous earth faults occurring should not be overlooked. Reference has already been made to this in my reply to Dr. Garrard. Breaking capacity also has already been dealt with. With reference to the replacement of fuses in wet weather, the lid is not kept open for any length of time, and light building constructions have been used over the fuses. Something in the nature of an umbrella is really all that is required on the few occasions when it may be necessary to open the lid in heavy rain.

I agree with Mr. Mellonie as to the importance of stability in the design of potential transformers and fuses, and would strongly support his recommendation for minimum sections of fuse wires and windings. The potential transformer, however, has seldom been used on protective systems and never on the balanced systems of protection, and although trouble with such a transformer is annoying it does not endanger the continuity of supply, provided it is correctly used. Its failure does not endanger the operators and hence it has not been given in the paper the same importance as current transformers. I agree with Mr. Mellonie's objection to the use of carbon-composition resistances. Attempts have been made, and are likely to be very successful, to combine the required resistance with the fuse itself, thus obviating the introduction of any additional piece of apparatus into the potential-transformer circuit. The problem is to use a fuse wire sufficiently liberally rated to avoid risk of injury due to mechanical weakness, and when this size and strength is obtained the fuse on the high-tension side of the potential transformer must not be expected to do more than clear faults on the high-tension winding—in other words, to protect the system from the transformer rather than to protect the transformer itself from overloads or short-circuits on the secondary. It is certainly of primary importance for all trip coils to be rated with a good safety factor. The no-volt trip-coil feature, however, is one which has not made for reliability of supply. On the other hand, the principal objection is the risk of it causing inadvertent tripping. This consideration would not lead one to expect much from an extended use of no-volt coils arranged to be open-circuited by relays on the several protective systems. The inadvertent operation of switches is sometimes more to be feared than the failure of a switch to trip when it ought to trip, and Mr. Mellonie's virtue in exposing failures might become irksome. Adequate periodic inspection of tripping mechanisms is advocated in preference.

Mr. Forrest's remarks are of great interest to me and I have already dealt with his criticisms relating to the duplication of circuit breakers. The adequate protection of circuit breakers which are unable to deal with fault currents owing to the increase in generating plant is a problem with which we are frequently faced, and the use of reactance in these circuits must be controlled to a large extent by local conditions. It is often preferable and more economical to replace the switchgear, utilizing the old gear in a more remote situation, on account of difficulties in voltage regulation. Experience has now taught us to allow a more reasonable margin in breaking capacity when determining the size of breakers for a new situation than was the case 10 to 15 years ago. Much attention has been given to the important problem of determining the most efficient speed of break in a circuit breaker. As Dr. Garrard mentioned, it is the subject of research at the present time and is one of those points on which further elucidation is pending. In the meantime, economic limits giving satisfactory results in practical service may be taken as between 5 and 10 feet per second.

Mr. Wilson would be treading on insecure ground in relying too much upon the ultra-sensitive setting of

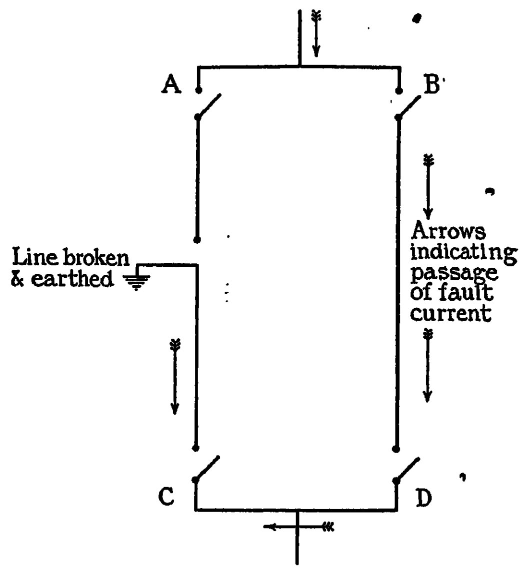

FIG. C.

relays. He makes no mention of how his light settings would behave on transformer protection, for instance, where a heavy magnetizing current-rush must be dealt with. Moreover, his advocacy of light fault-settings is contrary to his preference for parallel-feeder systems of protection, in which the fault-settings must exceed the normal load currents in order to prevent inadvertent operating of a switch at one end when opening by hand a circuit breaker at the other; and, even so, there are incidents in parallel-feeder protection where the sound cable is cut out instead of the faulty one. For example, in the event of an open circuit making a fault to earth on one side of the break only, as shown in Fig. C, the fault current will pass down the healthy line and switch B will trip out, leaving A closed, thus isolating the sound feeder and leaving the unearthed end of the faulty line alive. Mr. Wilson disapproves of using two existing cables on one split-conductor switch, on the ground that it involves the waste of an entire cable. This alleged

waste only appertains when one of the cables has broken down, in which case it is out of service anyhow. In those cases where there is no suitable alternative supply the sound line may still be used by the addition of isolating switches on each cable and the substitution of the split-conductor protection by a heavy overload setting.

Mr. Jones endorses the main points of the paper, and it must be admitted that the effect of the demands for safety in mines has had an all-important bearing upon the general improvement in switchgear construction throughout the whole electric supply industry, and it is opportune that one having so much practical experience should emphasize some of the significant exceptions which have come to his notice.

Mr. Taylor also refers to the possibility of an arc burning through the metal sheathing of switchgear, in accordance with his experience on cables. This point has already been touched upon. In the first place, owing to the elimination of foreign interference, the metal enclosure reduces the risk of internal failure. In the second place, the framework of the switchgear being of metal must make a good earth; and if it were possible for the arc to be maintained to earth there is very little risk of it not carrying sufficient current to operate some neighbouring overload release and thereby isolate the affected area. And thirdly, the metal enclosure of neighbouring sections of the gear renders it practically immune from injury, so that the fault is localized. Mr. Taylor's investigation into the use of metal-covered cables for very high-voltage service is on a par with the developments now proceeding on switchgear for corresponding voltages. His experiences also in regard to the damping effects of earthing resistances must have a bearing on the future policy, and I am glad he confirms that the damping effect will not be impaired by using the comparatively low ohmic value of the earthing resistances which are required to improve the stability of the neutral point and the protective gear.

In conclusion, it is gratifying to notice the marked change which has come about in the general acceptance of the metal-clad principles, particularly in the discussions at the Local Centres. My thanks are accorded to many speakers who have been kind enough to attribute this to my own personal endeavours, which after long years of opposition have actually led the principal opponents to acquire for themselves designs of the same type. However, it would be more correct to attribute it to a school of engineers, including users, who have from time to time furnished the results of experiences and designs and thus created the demands which have built up the practice at present characteristic in the largest power station equipment in this country.

DISCUSSION ON

"AUTOMATIC AND SEMI-AUTOMATIC MERCURY-VAPOUR RECTIFIER SUBSTATIONS."*

WESTERN CENTRE, AT CARDIFF, 1 DECEMBER, 1924.

Mr. J. W. Burr: After reading the paper, I am more than ever convinced of the desirability of the 50-period supply. All the author's troubles seem to arise from the fact that the supply in parts of his area is at 25 periods. There seems to be no difficulty in dealing with the distribution problems by means of static transformers. If, for any reason, there is a bad voltage-drop on a line running out from the substation, there is no difficulty in installing an automatic voltage regulator near the desired point to suit the particular drop. In regard to traction supply, I have yet to be convinced that it is desirable to install mercury rectifiers instead of an automatic rotary-converter substation. The author's substation appears to be very large. At Swansea the substations are about 20 ft. square, and by means of static transformers we are able to supply a demand at any individual substation up to 500 kW. Compared with the author's substations, this means a considerable saving.

Mr. W. J. Bache: Do the bulbs give any indication that they are approaching the end of their life? With regard to the provision of spares, I gather that it would be only necessary to have one set, instead of having a complete stand-by as in the case, say, of a 500-kW rotary substation. Where a severe short-circuit in a traction substation shuts down the whole of the plant, there are eight bulbs to start up again, and the first bulb switched in will be severely overloaded. How does the automatic plant bring the whole of the bulbs into operation?

Mr. A. J. Newman: Has the author had any experience with rectifiers used for conversion to direct current for purposes requiring wide variations of speed and possibly inching, such as dock crane work, cigarette-making machinery, and printing processes? With the general acceptance of the three-phase system as a standard for distribution, such experience would be extremely useful and would provide a happy solution to many problems often met with by a supply engineer.

Mr. F. Ellis: Can the author give the approximate cost per kilowatt of installation as against the ordinary

* Paper by Mr. G. Rogers (see page 157).

static substation, and state how the transformer losses compare? Does the mercury-vapour bulb give what might be called a direct or unidirectional current? I should be glad if the author would detail the cycle of operations taking place in the bulb from the a.c. side to the d.c. side.

Mr. W. A. Chamen: Mr. Burr has attributed the troubles experienced at Birmingham to the use of 25-period current, but I think that they were due to the use of direct current. It all depends upon the way the matter is looked at. Reference has been made to the springing up of residential districts in the Birmingham area. We have had a few such districts to deal with in South Wales, but our method of tackling the problem has been different. Many thousands of houses are lighted by current at 25 periods and I have lived for six or seven years in such a house. It is impossible to discover any flicker at all from 60-watt lamps used out of doors for street lighting. The system described in the paper might be usefully applied to places in South Wales where a direct-current supply exists and where a bulk supply might be required from 25-period current.

Mr. J. B. Higham: In Fig. 6 the 276-kW boosting-plant power-factor curve remains well above 90 per cent from quarter load to full load, while in the other two curves, for 92-kW and 660-kW lighting and traction plants respectively, it rises sharply to 90 per cent at about half load, afterwards following approximately the 276-kW boosting-plant curve. Is there any particular explanation for this? What purpose does the choke coil serve in the low-tension anode circuit? The flickering of lights on 25 periods can be considerably reduced by adopting the right type of shade or reflector for the particular lamp, or lamps, employed. Where direct lighting is employed the effect is particularly noticeable unless correct and scientific shades are fitted.

Mr. T. H. Haigh: Has the author given a 25-period supply to any of the Birmingham consumers without first informing them of the periodicity? My house has been supplied for 11 years with 25-period current, and I have not noticed any flickering; only ordinary common-sense shades, such as would be used on any good lighting scheme, were employed. The company with which I am connected has many thousands of consumers on the 25-period supply and has never had a complaint from them. Possibly they did not know that the 25-period system was being used.

Mr. C. T. Allan: I have had an even longer experience than Mr. Haigh of lighting at 25 periods and I have suffered no inconvenience. A case came to my knowledge of a local authority's 50-period supply being changed over to 25 periods without the consumers being aware of the change.

Mr. W. Nairn: I have no fault to find with 25-period lighting, provided the voltage is normal and that a little special attention is paid to the shades. As regards domestic appliances such as vacuum cleaners, cookers and radiators, a frequency of 25 is quite satisfactory. With regard to traction supply, I am rather doubtful about the desirability of using the automatic reclosing circuit breaker described by the author. In the event of a trolley wire falling to the ground, it is not desirable to have the supply restored immediately the wires are picked up. Probably the linesmen have instructions to open the feeder switch at the line end before handling the wire, but this means two sets of regulations on a matter which affects the safety of the public.

[The author's reply will be found on page 478.]

North-Eastern Centre, at Newcastle, 12 January, 1925.

Mr. L. C. Benton: The author's decision as given in the opening paragraph is correct, and I would go even further and say that in almost all cases where direct current is required, automatic converting plant is the best solution. He adds that "it is possible to carry automatic control to any extent," and in my opinion the increasing need for economy and greater reliability, in addition to the labour problem, will eventually result in not only the conversion but distribution and even, to a large extent, the generation of electricity being automatically controlled. The pioneer work on rectifiers carried out in Birmingham is only fully appreciated after visiting the substations referred to in the paper. The glass-bulb rectifiers in particular have a most unmechanical appearance and their operation with the peculiar coloured arc is both fascinating and weird. I consider that the author has made a good case under certain conditions for small-capacity rectifiers up to, say, 200 kW. No doubt there is a future, greater than is now realized, for rectifiers even of large capacity, as existing troubles will be eliminated as time goes on. Knowing the difficulties that other users of rectifiers have experienced, one wonders to what extent the success at Birmingham is the result of the very thorough manner in which the problem has been tackled. The author refers to the first automatic rotary converter substation in this country, which was installed at Liverpool some $2\frac{1}{2}$ years ago and which has been an unqualified success. An indication of the strides in automatic converting plant already made in this country is the decision of one of the London underground railways to install, in connection with a new extension, a remotely controlled rotary converter substation of 4 500 kW capacity with automatic gear control. Referring to the estimates given in the appendixes to the paper, I am strongly of the opinion that the figures given for rotary converters are excessive and that for capacities of 500 kW and upwards actual costs are decidedly unfavourable to rectifiers. The annual maintenance allowance given for bulbs seems to indicate frequent renewals and is many times the maintenance costs of rotary converters. Many rectifiers have been installed on the Continent; this is perhaps partly due to the less reluctance of the Continental engineer to use complicated and fragile apparatus. As no reference is made in the paper to interference with telephone circuits by rectified current, I should like to ask the

author if he has had any trouble of this kind and, if so, what steps have been found necessary to eliminate what can be a very disturbing influence. In view of the characteristics of rectifiers, is it possible to arrange for satisfactory parallel operation with rotary converters, especially if the latter be compound-wound? It is not possible to obtain power factor improvement with rectifiers as with rotary converters. "Forming" of the anodes is said to be essential. This is really a "warming up" process and yet excessive temperature is fatal, as evidenced by the need for continuous cooling by water or a fan in the iron and glass types respectively. What is the temperature of the anodes during normal operation, and what are the gases that have to be driven off during the "forming" process, or the impurities in the anodes that give rise to the gases which cause flash-overs? The author mentions that as the result of experience it has been found necessary to use reverse-current protection when bulbs are running in parallel, to avoid the flashing-over of one bulb causing a similar failure in the other. Is he satisfied that the speed of operation of the circuit breaker is high enough to give the desired protection? From the appearance of certain bulbs when in service it would seem possible that they might eventually "mirror" sufficiently to cause a flash-over. Has the author known this to happen, and, if so, what is the remedy? I have heard that there is a risk of failure if a bulb is thrown on to full load when first installed. Does this mean that a certain amount of "forming" is desirable with the bulb type? Can the author say what the life of a bulb operating at, say, full load would be in the event of the cooling fan failing? As I understand that flash-overs are usually the result of loss of vacuum, what effect has a failing vacuum on the efficiency of a rectifier? While describing the method of operation of automatic rectifiers the author remarked on the simplicity of the necessary gear. Whilst admitting that the absence of synchronizing apparatus is a good feature of rectifiers, I suggest that the automatic starting gear for rotary converters is also simple. It is the devices subsequently found necessary to add to give protection against service emergencies that cause the comparative complications. From the author's remarks it is evident that experience of rectifiers under load conditions has resulted in a gradual addition to the devices considered essential, and when one remembers the cooling arrangements, vacuum pumps and gauge, motor-generator set for striking the arc, no-load resistance and so on, one will realize that rectifiers require many accessories.

Mr. R. D. Spurr: We must not forget that Birmingham is handicapped by having a three-phase 25-period supply and cannot develop 4-wire a.c. distribution in outlying districts in the same manner that other places with three-phase 50-period supplies are doing. I do not agree with the author that direct current has distinct advantages over alternating current for domestic supplies and cooking, and although there are undoubtedly special cases where d.c. power is more suitable there are also cases where a.c. power is wanted when only direct current is available. The d.c. networks described are very small and we are told that, as the load increases, the rectifier substations are to be enlarged in size and increased in number. It is generally agreed that we are at present only touching the fringe of the domestic load in this country; it is also agreed that it takes quite a large number of domestic consumers to make up a 40 or 50 kW demand, but the scheme outlined in the paper does not appear to allow for future additions of any great magnitude before it becomes saddled with an unwieldy number of small converting units. The proposed subdivision of converting plant almost approaches the old house-to-house system of a.c. distribution which has gradually been displaced by larger and more efficient substations. I think that in estimate No. (2) of Appendix 2 for a manually-operated substation the cost of e.h.t. feeders and four low-tension feeders is excessive; if it is correct then an omission has been made in estimate No. (3). I cannot visualize the two estimates as affording equal facilities for handling equal loads, unless there are some local conditions very much in favour of estimate No. (3), and if so some allowance should be made or further explanation given.

Mr. T. Carter: What would otherwise have been a serious disadvantage to consumers of current for lighting in the author's area has been turned into a real advantage by the rectification of the current. To me the fluctuations in the light, even at the 40 periods of this district, are sometimes very noticeable, and at 25 periods I am told, although I have not had personal experience, that the effect is often really very trying. By means of rectifiers, the current supplied to consumers in and around Birmingham is a slightly pulsating one with a frequency of 150 per second, and the lighting must be very pleasing. Something has been said by previous speakers to throw doubt on the wisdom of putting down comparatively small substations; but, after all, it is what the consumer has to pay that makes the supply attractive or the reverse, and I should like very much to know what charge is made for lighting current and current for domestic use generally in the districts served by the rectifier substations. It would be interesting to compare it, for example, with the charges here, where the flat rate is 6d. per unit plus a meter rent. We have a special tariff also, under which, it is said, the charge is 1d. per unit for electricity; but I understand that this tariff includes some extras, and it is necessary to ascertain what the amount of the extras is before the real cost to the consumer is known. It is easier, therefore, to compare flat rates, and I hope that the author will give us some information on the subject.

Mr. H. W. Clothier: Where two or more rectifiers are employed in parallel, as shown in Fig. 9, four separate high-tension panels are used for each rectifier set. The size of these circuit breakers will be determined by the kVA to be dealt with during a short-circuit at the point in question, and, in a case like Birmingham, the switchgear for dealing effectively with this may be somewhat expensive. Would it not be possible to parallel the transformers and effect an economy by reducing the number of panels required? The paper is very useful in demonstrating the extent to which switchgear problems enter into modern systems of

supply. Whether a.c. or d.c. distribution is the more economical or advantageous system to adopt, time must determine whether the mercury-vapour rectifier is really more economical in the long run than the alternative rotating plant. The author emphasizes the simplicity of his static equipment. Whilst agreeing with him, I suggest that the automatic control apparatus for a motor converter can be made no more complicated, even when including all the relays necessary for fully automatic working, together with a discriminating system of locking out and reporting back to a central control station. The complication depends upon the function required; for instance, some motor-converter equipments provide for complete manual and semi-automatic operation of the plant, when so desired. The main item inherent in the two types of plant seems to be that the automatic synchronizing and starting equipment of the motor converter has its counterpart in the rocking and arc-striking equipment of the valves. The relays and general automatic gear on the control board are much the same. The author states that valves may flash over on an overload. How do they behave in the event of a short-circuit ?

[The author's reply will be found on page 478.]

SCOTTISH CENTRE, AT EDINBURGH, 13 JANUARY, 1925.

Mr. C. W. Marshall: In the summary of the paper, the author stresses the value of the rectifier as a d.c. feeder booster, which I believe to be its most successful application to power supply systems. He shows that as an economic proposition, the scheme followed by Birmingham is better than that of increasing the d.c.

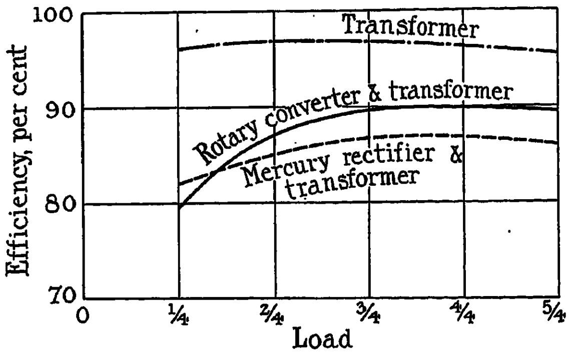

FIG. A.—Comparative efficiences of small rotary converters and mercury rectifiers with step-down transformers (5 000 volts a.c. to 440 volts d.c.).

low-tension copper, or of laying down large rotary-converter stations. He is, however, discreetly silent on the relative costs of low-tension a.c. systems and d.c. systems. There is always the possibility that some epoch-making invention will restore direct current to favour, and we must take the risk of that eventuality occurring. It is, however, a much simpler and cheaper matter to change from alternating to direct current than the converse. The steel-cylinder rectifier has not given very great satisfaction in this country, but on the Continent it has done very well, and both the A.E.G. and Siemens-Schuckert have developed steel-cylinder rectifiers for large outputs. It is significant, however, that both of these firms have adopted the glass-bulb rectifier for the capacities which Birmingham has standardized. The author has not made an exact comparison between the 92-kW rectifier and the rotary converter of corresponding size. As a matter of interest I took out some costs and figures for the corresponding small rotary converter, and I am satisfied that these would approach very near to those for the rectifier under the conditions existing at Birmingham. The efficiency is at least 4 per cent better at full load, and is as good at quarter load (see Fig. A). The price is about 5 per cent less, and the advantages of the rotary converter in overload capacity and in power factor are very marked. The main claim of Birmingham on behalf of direct current is that battery stand-by can be provided. I feel sure, however, that a purely a.c. system is more reliable than a d.c. one, even when there are batteries to fall back on in emergency. The standard economic argument (or apology) for direct current is that the percentage increase in capital required is so small that it is not worth serious consideration. This item should, however, be considered in conjunction with the following consequential increases in expenditure: Increased staff, maintenance and building charges on converting plant; decreased conversion efficiency; and increased initial and maintenance cost of meters.

Mr. E. Seddon: The application of the type of rectifier described in the paper is, of course, specially suited to stations operating at low frequency. The tramway supply referred to is of special interest, as this rectifier is an attractive proposition on the higher frequencies for such purposes; but the cost would, I think, operate against the rectifier for heavy traffic conditions requiring a large amount of power. It is of interest to me to know that the bulb lasts so long as 8 000 hours; I was of the opinion that the average life was very much less than this. In large power stations the installation of turbo-driven a.c. generators is now standard practice, and in consequence of this the extension to d.c. distribution has been curtailed. The universal application of electricity for all purposes makes it incumbent on the engineer to reduce the cost of production as far as possible, and in this respect the losses incurred in transmission and conversion are serious factors. In Edinburgh the transmission, conversion and distribution losses amount to 16 per cent of the total output to feeders, and about 75 per cent of the total output is converted to direct current. If we are to extend the d.c. system, we must find something which will be as efficient and reliable as the static transformer. Where the energy is generated at 50 periods per second, a.c. distribution, in my opinion, has no equal for cheapness and flexibility.

Mr. A. P. Robertson: I think that for traction the system advocated by the author has possibly some advantages, but I do not agree with him when he says

on page 157 that direct current has distinct advantages over alternating current for domestic supplies. I should like to ask what the advantages are. I have heard that alternating current is very dangerous to have in the house, but I never heard of any fatality that could be traced to the use of alternating current as against direct current, and if the author could give any concrete reasons for this statement I should like to hear them. I do not think that lighting at 25 periods is unsatisfactory. There is a very slight flicker, but this is overcome by ordinary shades, unless in a very small room where the ceilings and walls are white, but the flicker is not objectionable. The steel-cylinder rectifier is quite successful in certain ways, but I think that the glass-bulb rectifier is superior to it. The steel-cylinder rectifier has too much other gear connected with it, and that is a disadvantage. In addition the formation of the anodes is a great drawback. The glass-bulb rectifier, on the other hand, has no pumps and does not lose its vacuum. If left out of service it does not require to be re-formed, and the wiring is very much simpler. In regard to the automatic features of the steel rectifier given on page 159, after the oil switch is closed I do not see any provision for stopping the sequence of operation if the vacuum is not high enough. Then, again, the temperature of the cylinder is a very vital point and I see nothing to control it. Also, no provision is made for switching out should the vacuum fall, and loss of vacuum is the cause of most of the short-circuits and failures in steel cylinders. I believe that one of the causes of the success of the steel rectifier in Birmingham is, first, that it is a single cylinder on its own transformer; secondly, that it runs in parallel with a battery; and finally, that it is very seldom on full load. The glass rectifier, of course, has very great advantages over the other type, and these are obvious in reading the paper. Fig. 14 shows a substation of 276 kW feeding into an existing network. The author says that he feeds across the outers, and depends on the balancing from the nearest rotary substation. If the substation is more than 2 miles away this is not satisfactory unless there is a middle wire and a balancer of some kind. I am speaking of a rotary substation where the middle wire is left out periodically, and when the middle-wire switch is closed the balance is quite satisfactory. We in Glasgow have several substations with semi-automatic control, and the cost of that equipment is £150 per machine. The substation has all the good points of a fully automatic substation with the exception that it does not start up, and as the load on the substation is more than one machine can take satisfactorily at the peak we have a man in attendance, who puts in an extra machine over the peak and goes home when the load drops to the capacity of one machine. This machine runs day and night and is only shut down during the period that the man is there for cleaning. Another of our substations has no attendant at all; it is started up on Saturday after cleaning, which is done weekly, and left with no attendance unless outlying plant men happen to be passing. These men have instructions to enter every time they are near. We find that system perfectly satisfactory. For outlying districts, or where a district is being developed, I am of the opinion that a.c. distribution is best. Table A shows some figures which I took out for substations of about the same capacity as the installations detailed on page 172.

TABLE A.

Comparative Costs of Substations.

Static Substation, 300 kVA.

	£
Building, including site	400
300-kVA transformer	400
E.H.T. switchgear	250
L.T. switchgear, including 2 feeders	80
Cabling, etc.	200
	£1 230

No attendance required.

Rotary Substation, 250 kW.

	£
Building, including site	1 000
Rotary converter, 250 kW	1 800
E.H.T. switchgear	250
L.T. d.c. switchgear, including 2 feeders	360
Cabling, etc.	300
Semi-automatic gear	100
Capital cost of half time of man as he is only required to start and clean machine	1 000
	£4 810

Mercury Rectifier Substation, 276 kW.

	£
Building, including site	400
276-kW rectifier	2 246
E.H.T. switchgear	225
L.T. gear, including automatic gear	350
Cabling, etc.	50
	£3 271

I have omitted external cabling in all cases, because each case is different in this respect. Three 300-kW transformers will cost but little more than one rectifier substation, and I do not think that the attendance would cost very much. The feeders would be shorter, and there would be less loss in the copper.

Mr. W. S. Sawtell: I should be glad if the author would give some further information regarding the suitability of the rectifiers, described in the paper, for supplying a d.c. network which requires a 24 hours' service. This is somewhat different from the service anticipated by the author, inasmuch as on the system described in the paper is a ring of substations all interconnected; for that reason each and every equipment has a stand-by. On page 158 the life of the bulbs is given as 8 000 hours, and Mr. Seddon, during the discussion, gave 4 000 hours as the average life. If these sets are to maintain a 24-hour service daily, the system will be shut down once every 6 months as the result of bulb failures alone. This is rather serious, especially if one of these rectifiers be installed in a station without attendance and situated some miles from the nearest

depot. How long is allowed for changing a bulb, and what happens when a bulb fails? What are the chief reasons for failure, and what happens to the bulb if the protective switches fail to act when an external short-circuit occurs? Considering this matter from the aspect I have mentioned, I think station engineers will agree that the voltage regulator should have a compound chracteristic. I should be glad to know if the regulator described can be so designed. Mr. Robertson criticized the author's figures for the cost of his substations. I have not gone fully into the matter, but I notice that the cost of high-tension switchgear seems unusual. For instance, in Appendix 3 the figure of £323 includes the cost of 2 high-tension feeder switch panels, 1 busbar coupler switch, and 4 transformer switch panels, the average cost being £46. I think that the author would do considerable service by mentioning the name of the maker of this switchgear, as we must assume that he has found it satisfactory.

Mr. A. E. McColl: I cannot accept the author's statement that alternating current is unsatisfactory for domestic supplies. This seems to me to be a rather sweeping condemnation of the many efficient and satisfactory supplies given from 50-period systems. On the lower periodicity of 25, objection is occasionally taken to the use of alternating current because of what is termed the "objectionable flicker." The company with which I am associated have carried out experiments in order to determine if this "objectionable feature" can be reduced to negligible proportions. Our view is, therefore, that if scientific principles plus a little ordinary intelligence are applied to domestic lighting the bogy of flicker need not deter the consumer from adopting, or prevent the supply authority from developing, 25-period power for illuminating purposes. For the scattered urban areas which are indicated as being the main field for the employment of the glass-bulb rectifier, I do not see that there is any economic justification if 50-period alternating current is available. With alternating current we give supply from an essentially sound, efficient and satisfactory piece of apparatus, and why should we reduce the safety factor of the continuity of supply by introducing what seems to me to be an essentially weaker feature, viz. the glass-bulb rectifier? Perhaps there may be some justification for the use of the rectifier in certain cases such as acting as boosters on extensions of existing d.c. networks. Where an undertaking is committed to the laying down of a new low-pressure distribution system for domestic supplies, and alternating current is available, I see no justification for altering the system of supply. The rectifier appears to be a satisfactory piece of apparatus on isolated tramway routes with an infrequent car service, as it can be made automatic at a lower expenditure than is the case with a purely automatic rotary converter.

Prof. F. G. Baily: I think that Mr. Seddon is probably quite correct in his statements as to the life of the bulbs. Manufacturers are, however, working very hard extending the life of the larger bulbs. We had the same experience when the tungsten lamp was first introduced, and again when the gas-filled lamp was brought out, but once the initial difficulties were overcome very few complaints were received in regard to short life.

Mr. H. F. Hunt (*communicated*): As regards the retention of direct current in certain districts, and the general tendency in others for its replacement by alternating current, I think we ought to keep in mind the possibility, though admittedly remote so far as can be foreseen at present, that future generations may witness developments in electric lamps—not necessarily of the present filament or even vacuum-tube type—for which direct current alone will be suitable. Should such circumstances arise, many districts might have to revert to direct current with rectifiers or rotary converters, whereas Birmingham would be ready and would be saved the large capital cost of a double change-over.

Mr. G. Rogers (*in reply*): Mr. Burr is not convinced of the desirability of using automatic rectifiers for traction purposes. I can only say that I should like him to see the substations actually in operation and again carefully to examine the costs of this plant as compared with those of rotary converters.

In reply to Mr. Bache, bulbs do not give any indication when they are approaching the end of their life. Where a severe short-circuit occurs on the traction system, normally the feeder circuit breaker opens and clears the fault, and will reclose again only when the fault conditions are removed. It sometimes happens that the short-circuit is so severe that it also opens the overload circuit breakers protecting each bulb. These breakers reclose before the time lag of the feeder circuit breaker has expired. Should the main high-tension oil switch supplying a transformer be opened, then the one set remains out of service until re-started by manual operation.

In reply to Mr. Newman, I have had no experience of rectifiers on the particular work referred to, but the demands such as traction load, particularly on the peak, would be very similar to those made by crane work, etc. I should imagine that the bulbs would be entirely suitable for this class of work. The transformer losses are a little more for the rectifiers than for static transformers.

Mr. Chamen, with others, refers to the "troubles" experienced in Birmingham. I would say that these speakers are under a misapprehension. We are perfectly satisfied with the 25-period a.c. supply, and consider the d.c. supply to be the best that can be given for all domestic purposes. I note that Mr. Chamen agrees that where a d.c. supply exists, and where a bulk supply may be required from a 25-period supply, rectifiers may be used with advantage.

Mr. Higham raises the question of the power factor of the plant for traction and for lighting purposes. The difference in the figures is due to the different values of the reactance in circuit. The choke coil in each of the low-tension anode circuits is to allow of parallel running.

Mr. Nairn qualifies his approval of a 25-period supply by stating that the voltage must not vary and that special attention must be paid to the shades.

Mr. Benton questions the accuracy of the figures quoted in Appendix 2 for rotary converters. The figures given in the estimate were the ruling prices for the plant at the time the estimates were made. In regard to the use of reverse-current protection when the bulbs are running in parallel, this method has been adopted on later sets and at the moment I am not satisfied that the speed of operation of the reverse breaker is great enough to give the desired protection. Experiments are still being carried out in this respect. Occasionally bulbs mirror over, the mercury forming a deposit on the inside of the bulb. By applying light loads to the bulb it is possible to remove the film of mercury. With regard to the risk of failure, it is obviously a strain on a new bulb to switch full load on immediately and it is better to warm the bulb up gradually, starting with a low load and working up to full load. This process, however, is not absolutely necessary. The life of a bulb operating at full load in the event of a cooling fan failing, would depend on circumstances. A 230-volt bulb was subjected to full load for 1 hour without the fan running. The bulb became very hot, but no flash-over occurred and the bulb suffered no ill-effect whatever and is still in service. On the other hand we have had one case where the failure of the fan caused a flash-over in the bulb. It had been running on light load for some hours without the fan, but failed on the peak load in the evening.

Mr. Spurr draws attention to the small size of the three-wire lighting substations described in the paper. These substations, as now standardized, are capable of containing up to 750 kW of converting plant. In the areas now being developed by this means, this is likely to be sufficient for some years. Additional substations can be put down as in the case of static transformer substations.

I agree with Mr. Carter that the supply at 25 periods can be very trying, and I note his remarks that even at a periodicity of 40 the flicker is sometimes very noticeable. The charge to the consumer for a supply in the areas opened up by the rectifier substations is 4½d. per unit for lighting and 1½d. per unit for heating and power. I note that this compares very favourably with the flat rate of 6d. per unit at Newcastle.

In reply to Mr. Clothier, where rectifiers are employed in parallel the advantage of supplying each pair of bulbs with a separate high-tension switch is that it allows of the splitting-up of the unit, and in the event of a fault on one half the other half is available for service. With the type of switchgear used, the arrangement is not very expensive.

In reply to Mr. Marshall, I am convinced that for plants of small capacity the automatic rectifier substation is preferable to rotary converter equipment. I cannot agree that a purely a.c. system is more reliable than a d.c. one when provided with batteries to call upon in an emergency.

Mr. Seddon agrees that the rectifier for traction supplies in the case described in the paper is very attractive.

I would refer Mr. Robertson to the Annual Report of the Senior Electrical Inspector. The following is an extract taken from his report of 1922: " . . . of the medium-pressure and low-pressure accidents, 10 fatal cases were due to shock from alternating current at 250 volts or less, as against none from direct current. This is entirely in accordance with the experience of previous years." Referring to the automatic features of a steel-cylinder rectifier given on page 159, I agree that no provision has been made to stop the sequence of operations if the vacuum is not high enough. During the long period this set has been in service, however, no trouble has been experienced due to this. If the vacuum failed completely I would point out that the arc would not strike and the set would not go into commission. Provision can now be made for this feature, however, and has been described elsewhere in the discussion. Table A is interesting but it clearly shows the advantages of the completely automatic rectifier substation over the semi-automatic rotary substation which, according to Mr. Robertson, works out to £19 2s. per kW, against £11 8s. per kW for the completely automatic rectifier equipment.

In reply to Mr. Sawtell I would say that all the outlying substations mentioned in the paper for three-way supply give a continuous service. In some cases the network is run entirely separate from any other supply and under these conditions is quite satisfactory. With regard to the life of the bulbs, the 8 000 hours mentioned was the number of hours the test-bulbs had been in service at the time the paper was written. These bulbs are still in service and have now burned for over 12 000 hours. The average life of a bulb cannot be taken as 4 000 hours—it is considerably more than this. The voltage regulator described in the paper cannot be given a compound characteristic.

In reply to Mr. McColl, I must point out that the statement in the paper that alternating current is unsatisfactory for domestic supplies, distinctly referred to an a.c. supply at 25 periods.

I agree with Mr. Hunt's remarks. In the future there are bound to be great developments in the mercury rectifier. This may also apply to the use of thermionic valves for heavy-current work.

DISCUSSION ON

"THREE-WIRE DIRECT-CURRENT DISTRIBUTION NETWORKS." *

NORTH MIDLAND CENTRE, AT BRADFORD, 10 MARCH, 1925.

Mr. C. A. Gillin: On page 337 the author refers to a neutral conductor. This should not be too small, as in the event of faults it will have to carry the same current as the others. I think that the author lays rather too much stress on the current-carrying capacity of the cables. Even in the case of feeders, the size of the cable is chiefly determined by the voltage-drop. One has to arrange the feeders, no matter what the lengths are, so that the voltages at the feeding points are more or less equal, otherwise spare machines have to be run on separate bars, which necessitates running at a more or less inefficient rate, particularly on the larger machines. Referring to the "Method of Laying," on page 339, I do not agree that any saving in capital charges results by the use of conduits. Conduits have their uses, but their abuses appear to me to be more prevalent. There is a tendency to put down more conduits than may at present be necessary, and the extra cost of these added to the extra cost of their installation—for example the extra depth of excavation to get a decent run, in which case one often has to go three times as far down as one would with direct-laid cables—adds from 30 to 70 per cent to the cost of the job. The capital charges for the loan period of 25 years, the period granted by the Electricity Commissioners for mixed systems, at 4½ per cent interest and 3½ per cent accumulative sinking fund amount to 7·07 per cent per annum, and it is only a matter of a few years for a payment at this rate to become greater than the cost of opening up the ground again. We then have a further advantage in that it is possible to lay additional feeders in the same trench for a considerable portion of the route, and of thus reducing future annual capital charges. There is another point about the conduit system. I notice that the author mentions that in his opinion it is not necessary to put concrete round a duct, but generally speaking I think it is very necessary, although this increases the cost of the job. In addition it seems to lead outside contractors to think that there is debris to remove, and it incites them to break into the concrete surrounding of the duct, the result being that the number of faults is greater than in the case of a cable laid direct. Item 4 mentions "less depreciation," but I think that there is *more* depreciation in cables laid in ducts unless they are run at a lower current density. For example, there is trouble due to the lead cracking at the joints, and also trouble due to chemical action on account of water, it being almost impossible to exclude water from the ducts, and the chemical combinations that the water has gathered up in its progress through the ground to the ducts attack the lead sheaths. On page 340 the author refers to the life of cables. In Bradford we have unarmoured cables laid direct in the ground and covered with jute, well compounded, that are as good to-day as when they were laid 35 years ago, and we never have any trouble with them. In fact I should say that they are better than new cables—the present-day cables—made for the same pressure. On page 344 the author refers to the necessity, or advisability, of making a three-core cable dead when connecting up services, but I think that this is quite unnecessary. I have never had a cable made dead for this purpose, and I have had thousands of services made on multicore live cables. An exception is the case of a cable the insulation of which has greatly deteriorated, due to the cable carrying a heavy fault current, which results in the insulation crumbling away whenever the lead sheathing is taken off. Even in that case services are often made on that particular cable, although I will admit that rather extraordinary precautions have to be taken for the safety of the man and of the supply. The author seems to be a great advocate of single-core cables. I quite admit that they possess many advantages. In fact I have on many occasions advocated their use, but there is nothing better than multicore cables, from the point of view of economics, space occupied, and design of good systems. I agree that, for feeders of 1 sq. in. and over, single-core cables should be used. On page 344 also the author refers to fuse boxes and the fact, or the possibility, that they reduce the reliability of the system. Fuse boxes may do so, but fuse pillars certainly do not. They greatly restrict the risk of breakdown, and I should always advise that as many as can be afforded should be used.

Mr. R. W. Grubb: I am in favour of the use of three single-core cables instead of a three-core cable. Our system consists of practically all single cables for distribution, and they are found especially useful in locating faults. It is possible to put in a four-way distribution box without making the distributors dead, whereas with a three-core cable the risk is too great. Although the cost of three joint boxes instead of one for a three-core service, and the greater cost of two single cables over a two-core cable increases the cost, yet one has a greater feeling of security and ease of mind, and further it is safer to open out a tee joint box on a live single cable than on a live three-core cable. At the same time three joint boxes necessitate opening out more ground, which is a disadvantage in a congested pavement. We invariably find gas and water mains and services in our way in the pavement, and only large gas and water mains are laid in the roadway. At the moment, while laying cables, we are doing the gas department a great service by finding service pipes that fall to pieces when the ground is removed. The author mentions fuses in feeder pillars. We have found that copper wire fuses

* Paper by Mr. H. W. Taylor (see page 337).

have a tendency to waste away, and although they are put in of a sufficient size to carry a large overload they need frequent examination. I am not in favour of concrete being laid on the top of the ducts, and we have had several cases of other departments driving wedges through concrete, making holes in ducts, and in some cases piercing the cable. Some time ago a dead earth came on the positive side of our system, as shown by the earth switch dropping and the indicator lamps burning brightly, but the central-zero ammeter showed no reading, and the resistance (automatically inserted when the earth switch drops) became heated, showing that current was passing. A d.c. ammeter was inserted in the circuit as a check, but registered nothing. An a.c. ammeter was substituted and was found to read the amount that usually flows through the resistance when an earth is on the system. The earth was traced to a certain feeder by making and breaking the earth switch, and certain suspected consumers were asked to switch off their motors temporarily. Eventually the earth went off when a certain motor was shut down, and the cause of the earth was traced to one of the windings on the armature rubbing against the pole-tips.

Mr. W. W. Firth: The author advocates three single cables for feeders and three-core cables for distributors. Personally, from the point of view of current-carrying capacity, I think that the reverse is better, as generally one feeder is supplying several groups of distributors, any set of which may be overloaded and yet the feeder only lightly loaded. The number of faults on distributors is much greater than on feeders, and these are more easily repaired with single-core cables, whilst, due to the fact that only one core is damaged by the fault, the number of consumers likely to be affected is reduced. I should like to know the author's reason for advocating (on page 347) three-core distributors where three-core feeders are used. Provided the whole of the cables are at least lead-covered, and thereby the whole system is bonded, I see no great advantage from the point of view of fault localization. If it comes within the scope of the paper, I should be glad to hear the author's experience in using the enclosed type as against the open type of fuse.

Mr. W. H. N. James: It seems to me that the calculations dealt with in the Appendix cannot be carried out with much accuracy because of the difficulty in obtaining the requisite data; in particular, it is extremely difficult to get adequate information in regard to the load, the probable value of which it may be necessary to estimate for a time several years ahead. This being the case it occurs to me that possibly a certain amount of simplification might be made in the formula which is reached towards the end of the Appendix without sacrificing accuracy to any important extent. This view is strengthened by the fact that if the total annual cost incurred on account of the cable is plotted against the area of cross-section, the curve is, as a rule, flat near the most economical area of cross-section, since the increased fixed cost resulting from the larger cross-section is largely balanced by the decreased running cost on account of the energy wasted. Now the formula given in the paper for the total annual charges includes three terms, those numbered (1) and (2) giving costs that increase proportionally with the resistance of the cable (i.e. they are inversely proportional to the area of cross-section of the cable) and it would seem that term (2), which represents the annual cost incurred on account of the extra plant needed to supply the energy waste in the cable, is not likely to be more than 5 per cent or, at the most, 10 per cent, of the first of the two terms under consideration, and would not involve great inaccuracy if neglected. Coming now to the last term dealing with the annual charge on account of the cost of the cable and laying, this afternoon I plotted list prices for a number of sizes of cable against the corresponding area of cross-section and found that for low- and medium-pressure cables the resulting graph was a straight line passing very nearly through the origin, showing the annual fixed cost, for sizes likely to be used, to be practically proportional to the area of cross-section. Further, it would seem that the cost of laying would increase very slowly with the area of cross-section, thus giving a very flat curve which would have little influence on the most economical area of cross-section. These points being accepted, the formula given by the author can be simplified into one of the type

$$\text{Total annual cost} = \frac{X}{A} + YA$$

where A is the area of cross-section of the cable and X and Y are omnibus constants compounded of the constants mentioned in the paper and can readily be evaluated. Differentiating this expression with respect to area and equating the result to zero, the condition for the most economical area of cross-section is found to be $A = \sqrt{(X/Y)}$ and it appears that this will give all the accuracy needed.

Capt. J. E. Fletcher (*communicated*): The economic value of any system is in a large measure determined by the flexibility of that system, and it is therefore essential, where large capital costs for cabling are involved in places where the electric loads are likely to migrate, that very careful and intelligent studies be made "on the spot" with a view to determining the likely growth of development during a period of years. Inquiries of land agents, surveyors, municipal engineers and the like frequently enable information to be obtained as to the opening up of new districts, factories, etc., which all goes towards settling the problems of what size of cable should be provided at present and/or in a definite number of years. When all the possible information has been obtained the question of costs of provision can be intelligently studied and the most economical cable provided. In all such studies, however, a margin should be allowed for unforeseen development. In the case of feeder cables to the so-called "nodal" points there seems —without much examination—little doubt that the system adopted should be as flexible as possible for the following reasons: (*a*) That it is not economical to lay down cables much in excess of a 10-year requirement; (*b*) that it is desirable to build up a system gradually and so extend the capital charges over a number of years; (*c*) that the various improvements in the manufacture of cables from time to time may be made use of; and (*d*) that it is a costly matter to open out in situ

pavings. A duct system, then, appears to be the solution and the only question arising is how many ways should be provided at the outset. To solve this question, as I said before, is to make a comprehensive survey of the entire area to be served and compute in quinquennial periods the probable customers and their estimated consumption. The same remarks apply equally to the distributor cables. Greater flexibility and greater immunity from serious troubles go hand in hand with a larger number of cables which are the outcome of a system gradually built up. I agree with the author that three single-core cables should be used mainly from the point of view of reducing to a minimum the number of faults and consequently the inconvenience to the consumer (a most vital point). The current-carrying capacity of the individual cables as shown in Table 1 is less in a duct than when laid direct in the ground. It is assumed that the figures are based on "dry" ducts, but in practice it is found that it is almost impossible to maintain a dry duct system; if there is water in the vicinity of the track, it seems to find its way into the system. The ideal system is to lay the ducts in such a way that, if any water does get in, it drains into the surface boxes or manholes. This, however, is seldom possible in large towns and in many cases the ducts have necessarily to be laid in a concave fashion. The result is that, should water get in, it remains unless it escapes by way of the joints. I do not think that much trouble from freezing may be feared in this country, as the frost does not penetrate so far into the earth. Avoidance of concave and convex layings in any one section of ductwork is necessary, as should a second cable be required in the same duct there is little chance of getting it in. The value of the spare duct space is therefore lost. To overcome the difficulty an inspection chamber or a split coupling should be provided at the junction between the concave and the convex turning. Ducts laid with a cover of 2 ft. with the present-day roadway construction should be immune from danger of crushing without the use of concrete. When drawing lead-covered cables into conduits, a good plan is to cover them slightly with petroleum jelly; this not only affords a protection against electrolysis but serves as a lubricant. At this point I should add that it is sound engineering practice to bond all lead cable sheaths together and earth them at frequent points. The author says that in the case of cables laid direct in the ground: "A fact that becomes quickly apparent is the ease with which such work can be carried out." I should like to add a word of warning here. Although it may be easy to bury the cable it is just as important that every care should be taken to safeguard other undertakers' property by giving a proper and safe clearance as it is to safeguard the cable itself. With regard to Tables 3 and 4, and with special reference to the figures quoted in connection with the conduit system, I do not think that the figures are properly proportioned, as Table 3 actually includes what may be termed "spare plant," inasmuch as the figures cover the cost of providing spare capacity for a future cable, and Table 4 takes the credit of this. Conversely we might provide spare cable in the case of cables laid solid in bitumen or direct in the earth in the first place. In conclusion the author advocates the use of ducts for feeder cables and also earthenware conduits for service cables in order, amongst other reasons, to reduce the costs of repairing faults. It is therefore not at all clear why he does not advocate the use of similar plant for distributor cables, assuming that all in situ pavings in these days may be regarded as expensive to reinstate.

Mr. H. W. Taylor (*in reply*): Few points have been raised in this discussion which have not been dealt with in my reply to previous discussions at other Centres.

The instance which Mr. Gillin gives of the life of an unarmoured lead-covered, served and compounded cable laid direct in the ground is very interesting and I think that more use could be made of this type of cable in many instances, with a considerable reduction in the cost of extensions.

I am pleased that Mr. Grubb has also experienced the feeling of increased security which one obtains with a single-core system. Opinion seems to differ as to the advisability of covering conduits with concrete. I have personally experienced more cases of damage to cables in conduits so protected than in those unprotected.

The chief advantage of the single-core lead-covered system is that when an earth fault occurs the supply can usually be maintained owing to the trouble being confined to one cable. This advantage is to a large extent nullified by the introduction of multicore cables in any part of the network, as faults on this type of cable are rarely confined to one core. It is for this reason that I consider the single-core distributor cannot show sufficient advantages over the three-core to warrant its higher cost, if multicore cables are used for feeders. Replying to Mr. Firth's other question, in my experience I have found the open-type strip fuse to be preferable for continuous loads higher than 150 amperes.

The formula given by Mr. James will in many cases give sufficiently accurate results. As I stated in the paper, practical considerations generally prevent a hard-and-fast application of any such formula. In dealing with any specific case, when the only variable quantities are r and C_2, the formula which I give then assumes the simplified form: Total annual cost $= K_1 r + K_2 C_2$, where K_1 and K_2 are constants made up of the other constants mentioned.

I would point out to Mr. Fletcher that the costs shown in Table 3 for the conduit system include only the cost of the conduits necessary for the feeder concerned and do not include spare ducts. Table 4 shows the cost, exclusive of cable, of replacing the cable with one of larger size. Where circumstances warrant, it is often advisable to lay additional ducts, but this of course should not be included in the cost of the original cable. I only advocate the use of conduits for a service over that part of its route in which it would be expensive to repair a fault in a cable laid direct or solid, such as in crossing a main road or under a terrazzo floor in a consumer's premises, etc. The number of times that conduits used for distributors would have to be broken in order to make service connections would greatly limit their usefulness.

THE SIXTEENTH KELVIN LECTURE.

ELECTRIC FORCES AND QUANTA.

By J. H. JEANS, M.A., D.Sc., LL.D., Sec. R.S.

(*Lecture delivered before* THE INSTITUTION, *5th February*, 1925.)

It is just about twenty-five years since Lord Kelvin spoke of "two clouds" obscuring "the beauty and clearness of the dynamical theory which asserts light and heat to be two modes of motion." The clouds which Lord Kelvin saw as clouds no bigger then a man's hand have grown until they have almost filled the firmament: little can now be seen of the beauty and clearness of the dynamical theory of which Lord Kelvin spoke. The old dynamical theory has given place to the new theories of relativity and of quanta; what Lord Kelvin thought were transient clouds shortly to melt away have proved to be new theories in process of growth; the "beauty and clearness" he saw under these clouds was mostly a mirage.

I have chosen as my title "Electric Forces and Quanta," the two halves of this title corresponding roughly to the two new theories, and I propose to try to sketch out the changes these theories have introduced into our conception of fundamental electrical processes. Let us consider electric forces first. Lord Kelvin, following Maxwell and Faraday, regarded an electric force as evidence of a stress in the ether. An ether can transmit two kinds of stress, one arising from a state of static strain and the other from a transfer of momentum; these were supposed to be electric and magnetic forces respectively. Or, to put the matter in another way, an ether can possess two kinds of energy, potential and kinetic; these were identified with electrostatic and electromagnetic energy respectively. This mechanism of stresses in the ether was devised in order to escape the necessity of "action at a distance." The ether itself had no doubt originally been brought into existence for quite other reasons—to provide a nominative to the verb "to undulate," according to the late Lord Salisbury—but these other reasons were no longer of much cogency. Light, whether an undulation of a medium or not, was admittedly an electromagnetic phenomenon, and the electromagnetic theory of light had already made it clear that any mechanism which could account satisfactorily for electric and magnetic forces could carry the whole of the undulatory theory as well. It was because Maxwell and Faraday had disliked "action at a distance" that the ether continued in existence at the end of the nineteenth century.

A MEDIUM, OR ACTION AT A DISTANCE.

Nevertheless, the conception involved a difficulty which seems to have troubled the nineteenth century physicists not a little. The energy of the ether could represent all kinds of electromagnetic energy, but could represent nothing else. Gravitational energy, for example, could not be interpreted as ethereal energy, for the only two types of energy which the ether could hold were already allotted to electric and magnetic energy respectively. It is true that attempts were made to interpret gravitation as normal waves of compression or as pulsations of very high frequency in the luminiferous ether, but such explanations never survived comparison with facts, and those who tried to explain gravitation had to fall back either on a new and entirely separate ether or else on action at a distance. If action at a distance had to be called in to explain gravitation, it might just as well be allowed to explain electromagnetism as well; there seemed to be no logical resting-place between two ethers and none. But the need for multiple ethers simultaneously filling space aroused suspicions in those who were conversant with the history of science. In an earlier century, according to Sir Joseph Larmor, "aethers were invented for the planets to swim in, to constitute electric atmospheres and magnetic effluvia, to convey sensations from one part of our bodies to another, and so on, till all space had been filled three or four times over with aethers. It is only when we remember the extensive and mischievous influence on science which hypotheses about aethers used formerly to exercise, that we can appreciate the horror of aethers which sober-minded men had during the eighteenth century."

In time it became clear that the only thoroughly satisfactory possibility was no ether at all. First the development of the theory of relativity gave its deathblow to the old luminiferous ether of Lord Kelvin, Maxwell, and Faraday. The main result of this theory can be stated in the form that all the phenomena of Nature go on precisely as though there were no ether. This does not of course abolish the ether; it shows the conception of an ether to be superfluous and perhaps even a little bit ridiculous—for it is ridiculous to fill the whole of space with a medium and then agree that everything goes on just as if the medium were not there—but it does not show it to be illogical.

THE EXISTENCE OF AN ETHER.

To the question, "Does an ether exist?" science is still unable to give a definite answer. The question, "Does the ether exist?" if the ether is taken to mean the luminiferous ether of Maxwell and Faraday, ought almost certainly to be answered in the negative. Speaking for a moment in the language of technical mathematics, the reason is that all the phenomena of Nature are invariant to the Lorentzian transformation

(the transformation to axes moving with a uniform velocity), whereas the physical properties allotted to the ether by Maxwell and Faraday are not invariant. Let E and H denote the electric and magnetic force at a point in the supposed ether, then $E^2 - H^2$ (the integrand in the action integral) is invariant, so that all properties which follow from the principle of least action are independent of the motion of the observer. These are of course the dynamical properties of the system. But $E^2 + H^2$ is not invariant, so that the phenomena which follow from attributing energy to the ether at a rate $(1/8\pi)(E^2 + H^2)$ per unit volume are not the same for a moving observer as for a stationary one.

Of the six components of stress attributed by Maxwell to the ether only three are invariant, so that electromagnetic phenomena, if explained in terms of ether stresses, call for stresses which are not the same for a moving observer as for one at rest, even though the observed phenomena are absolutely identical. For example, if magnetic forces are of ethereal origin, then the forces observed by a moving observer must be of quite different nature and origin physically from those observed by an observer at rest. If the latter observer's forces are produced by Maxwell's mechanism, the former's cannot be. To take the simplest example: an observer moving through a stationary electrostatic field will in actual fact observe magnetic forces just as much as if the field moved past him, yet the ether at every point of his path possesses no kinetic energy and so, according to the Maxwell-Faraday conception, could show no magnetic forces. The old Maxwell-Faraday ether had in some way to provide a duplicate mechanism for a single phenomenon, the magnetic force arising from an electric charge—and similarly for most other phenomena. No one has ever shown that it is capable of doing this; but even if they had, the duplication of mechanism to produce a single phenomenon is so contrary to the usual workings of Nature that there is not much risk in dismissing the old ether to the lumber-room.

Thus we may be confident that if an ether exists, it must be something very different from the Maxwell-Faraday ether. It must probably be thought of as a four-dimensional structure and must be more subjective than the Maxwell-Faraday ether. Each of us must carry his own ether about with him, extending through all space and all time, much as in a shower of rain each observer carries his own rainbow about with him. Whether such a structure, if it exists, ought to be called an ether, others must decide.

We may remark, in passing, that the conception of an ether has always made a special appeal to the practical, one might almost say engineering, type of mind which we associate with the leaders of British science. While our own physicists have asked for Nature to be reduced to a machine transmitting tensions and stresses, the more metaphysical minds of the Continent have usually been content to accept action at a distance as an ultimate explanation of natural phenomena, or at least to regard such an explanation as being in every way as final and as satisfying as an explanation in terms of a medium. It was something more than a coincidence that Newton, Kelvin, Clerk Maxwell and Faraday were all British, while Boscovitch, Einstein and Weyl are not.

Four-Dimensional Geometry.

The paper which practically abolished the ether as a serious scientific hypothesis was published by Einstein in 1905. Ten years later he published a second paper which may be said to have shown us how to get on without either an ether or action at a distance. His first paper, as afterwards interpreted by Minkowski, had shown that all the phenomena of electromagnetism might be thought of as occurring in a continuum of four dimensions—three dimensions of space and one of time—*in which it is impossible to separate the space from the time in any absolute manner*. You may separate them in one way, but you will find that I separate them differently, and in the end we shall both agree that no objective separation is possible.

Einstein's second paper showed that the phenomena of gravitation could be explained on the supposition that the geometry of this four-dimensional continuum was not of the ordinary Euclidean type. The con-

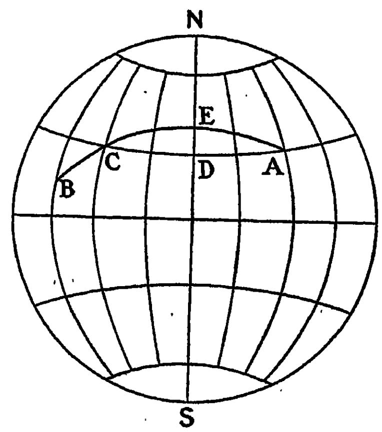

Fig. 1.

tinuum was supposed to be affected by kinks and twists in the neighbourhood of gravitating masses, and it was these, and not a "gravitational force," that threw a particle out of a straight course. It became just as inaccurate to say that the sun attracts the earth as to say that a bowl on an uneven bowling green is attracted or repelled by the other bowls. In this curved space the path of a particle is always a geodesic—the most direct distance between two points—and this may have very different properties from a Euclidean straight line.

We must, of course, remember that the paths we are discussing are in a four-dimensional space—if we were speaking of ordinary paths in three-dimensional space, it would clearly be ridiculous to say that the curved orbit of a planet provided the most direct path from perihelion to aphelion; it is only when we allow for the motion in time as well as in space that the statement becomes reasonable. We can get rid of most of the

motion in time by supposing our planet, or other body, to move with enormously high velocity, and then the path described actually approximates to a straight line, which is now the most direct path even in three-dimensional space.

We can gain some conception of the main features of Einstein's geometry from the analogy of spherical geometry; the curved surface of our earth provides a fair two-dimensional analogy to Einstein's curved four-dimensional space. To one who thinks in terms of "parallels" of latitude and longitude, or who studies geography on a Mercator chart, the most direct course on our earth's surface looks oddly curved: it is always a surprise to the unsophisticated traveller that the ship taking him from Southampton to New York (say from A to B in Fig. 1) turns a bit to the north on rounding the Lizard, while the great circle course on the ship's chart (A E C B in Fig. 1) looks very much as if the ship were describing an orbit about a centre of attraction in the middle of the Sahara.

If Einstein was able to avoid the evils both of action at a distance and of an ether in the gravitational problem, there would seem to be no reason why they should not be similarly avoided in the electromagnetic problem which specially interests us to-night. Not only is there no reason why this should not be done; it actually has been done. In 1918 Weyl pointed out that the geometry of Einstein was not the most general geometry which conformed to the relativity condition. Space could be distorted still further in ways unimagined by Einstein, these further distortions of the four-dimensional space being specified by the six components of a vector. Now the significant thing is this. On calculating the relations which must hold between the six components of the vector in order that the relativity condition may be satisfied, Weyl finds equations which are precisely identical with the electromagnetic equations of Maxwell, the six components in question now appearing as the three components of electric force and the three components of magnetic force.

Weyl's Electromagnetic Theory.

It is not easy to explain in non-mathematical language what is the essential difference between Weyl's space and the old Euclidean space. We can best attempt it by treating Einstein's space as a half-way house. Returning for a moment to the two-dimensional analogy provided by the earth's curved surface, we know that the lengh of a degree of longitude decreases as we recede from the equator; the ship turns north on its voyage from the Lizard to New York in order to take advantage of the shorter degrees of longitude up north. The planet going round the sun describes a curved path for a similar reason. According to Einstein's theory a measuring rod changes in length as it moves about in a gravitational field—a two-foot rule is no longer two feet in length if taken from the earth to the sun; it is because of this that the wave-length of the light represented by a definite spectral line when emitted at the sun's surface is different from that of the same light emitted on earth. The length of the rod depends only on its distance from the sun, being, in fact, proportional to

$$\left(1-\frac{2\gamma m}{rc^2}\right)^{-\frac{1}{2}}$$

where γ is the gravitation constant, m the mass of the sun, c the velocity of light, and r the distance from the sun. But in Weyl's space the length of such a rod does not depend solely on its position: it depends also on the path by which this position has been attained. A rod of length l displaced parallel to itself through a distance dx, dy, dz, dt in the four-dimensional continuum may be supposed to experience a change of length dl defined by

$$dl = l(Fdx + Gdy + Hdz - \Psi dt)$$

where F, G, H, Ψ are quantities which need not at present be specified. If the rod is taken a journey from P to Q its whole change of length will be given by

$$\log\frac{l_q}{l_p} = \int_P^Q (Fdx + Gdy + Hdz - \Psi dt).$$

In Einstein's geometry the integrand is necessarily a perfect differential, so that the value of l_q/l_p depends only on the position of Q and P and not on the particular path selected from P to Q; the condition that this integrand shall be a perfect differential is expressed by the six equations

$$\frac{\partial H}{\partial y}-\frac{\partial G}{\partial z}=0 \qquad -\frac{\partial \Psi}{\partial x}-\frac{\partial F}{\partial t}=0$$
$$\frac{\partial F}{\partial z}-\frac{\partial H}{\partial x}=0 \qquad -\frac{\partial \Psi}{\partial y}-\frac{\partial G}{\partial t}=0$$
$$\frac{\partial G}{\partial x}-\frac{\partial F}{\partial y}=0 \qquad -\frac{\partial \Psi}{\partial z}-\frac{\partial H}{\partial t}=0$$

In Weyl's geometry, on the other hand, the integrand $Fdx + Gdy + Hdz - \Psi dt$ is not a perfect differential, so that the quantities on the left-hand of the equations just written down do not vanish; they have values a, b, c, X, Y, Z different from zero, so that

$$\frac{\partial H}{\partial y}-\frac{\partial G}{\partial z}=a \qquad -\frac{\partial \Psi}{\partial x}-\frac{\partial F}{\partial t}=X$$
$$\frac{\partial F}{\partial z}-\frac{\partial H}{\partial x}=b \qquad -\frac{\partial \Psi}{\partial y}-\frac{\partial G}{\partial t}=Y$$
$$\frac{\partial G}{\partial x}-\frac{\partial F}{\partial y}=c \qquad -\frac{\partial \Psi}{\partial z}-\frac{\partial H}{\partial t}=Z$$

These are precisely Maxwell's electromagnetic equations, F, G, H being the components of the magnetic vector potential, and Ψ the electrostatic potential. Turning back, we see that F, G, H and Ψ are determined at any point by the rate at which a measuring rod of unit length changes its length as it passes through that point.

When Einstein explained gravitation in terms of curvatures and special metric properties of space, the equations of his theory were found to be different from

those of the old Newtonian theory. It was accordingly possible to make an observational test between the two theories, and this decided immediately and conclusively in favour of the theory of Einstein. There is no hope of establishing the truth of Weyl's theory in a similar way, for, as we have just seen, the equations to which it leads are precisely identical with the already universally accepted equations of Maxwell. Weyl's theory can only be judged by its inherent plausibility or the reverse.

Judged by this standard, everything seems to be in its favour. The luminiferous ether failed partly because it left no room for gravitation, partly because its mechanism had to be supposed to be too elaborate for the facts to be explained. The hypothesis of an ether led us to anticipate a whole series of different phenomena corresponding to different velocities through the ether, so that when these were not forthcoming, its advocates were compelled to elaborate a complicated theory by which all the forces of Nature were in collusion to make these different occurrences appear the same to us. The Einstein-Weyl geometrical theory escapes both these reproaches. Both gravitation and electromagnetism fit perfectly naturally into their places. These two systems of forces correspond exactly and completely to the ways in which a four-dimensional geometry can differ from the simple geometry of Euclid. The observed forces of gravitation and electromagnetism correspond exactly to the most general forces which are possible, if "force" is interpreted simply as an illusion arising from a crumpling up of space. Consequently the observed phenomena of Nature are precisely those which ought to be observed —not one is missing and neither is there room for a single one more. There is now no collusion among the forces of Nature to conceal a whole series of unobserved phenomena: indeed, there could be no concealment because there is nothing to conceal. By its simplicity, its completeness, and its perfect agreement with the observed phenomena of Nature, the theory seems likely to take its place as our final interpretation of the "forces" of Nature.

We now see that the universe of Euclid, in which parallel lines never meet and in which two sides of a triangle are always greater than the third, was a simplified ideal universe. In the same way the universe of Aristotle and Plato, in which space and time are permanently distinct and essentially different in their natures, was a simplified ideal universe. Both universes were too simple to fit the facts; remove the unwarranted simplifications and we are left with a universe the geometrical properties of which are expressed by such equations as Einstein's gravitational equations (to which Newton's inverse square law gives a good approximation) and Maxwell's electrodynamical equations. Thus geometry, cleared of *all* unjustifiable assumptions, transforms itself into mechanics, both gravitational and electrodynamical. A being who was born without any one of his five senses, but with unlimited geometrical reasoning powers, could deduce the general nature of the actual world without any experience of reality: he would anticipate that landslides, earthquakes, thunderstorms, and auroræ would occur; but he would know nothing about "forces," and would regard these phenomena merely as geometrical necessities.

Atomicity.

Although generalized geometry can predict and explain all the systems of forces of the universe it has its limitations; there are features of the actual universe before which it stands powerless. Nothing in geometry can explain the essential differences between positive and negative electricity, or the atomicity of electric charges, so that the whole inner structure of matter, including the whole of chemistry, would be outside the scope of the intuitions of our supposed geometer.

Electric charges are a consequence of, or at least are associated with, a curving or crumpling of space, but so far as pure geometry goes there is no restriction on the extent of this crumpling, so that our geometer, reasoning from geometry alone, might expect to find charges of all possible amounts, whereas in actual fact electric charges occur only in multiples of a definite unit, the charge of an electron. It is clear, then, that there is something more than geometry underlying the phenomena of Nature; the whole phenomenal universe may be geometry with restrictions if we like, but not merely the geometry which is obtained by generalizing the geometry of Euclid until we can generalize no further. Space can be crumpled up qualitatively in all the ways known to geometry but not quantitatively; the uniformity of electronic charge must in some way represent an absolute restriction on the measure of the crumpling.

Each particle of matter—each electron, let us say—occupies one point of space at any one instant of time, and the succession of these points will form a line in the four-dimensional space-time continuum—the "world-line" of the electron. In the neighbourhood of this world-line there is a deformation of the continuum due to the existence of the electron.

The near approach of two electrons or of any two charged particles is represented by a near approach of their world-lines in the four-dimensional continuum. Each world-line is surrounded by its associated deformation, and in regions in which the world-lines are near to one another the adjacent regions of the continuum will be doubly deformed.

A priori there are two possibilities open. The first is that the two deformations are merely additive, just as, when two ships approach, each making its own wash (or deformation of the surface of the sea), the height of wash at any point is the sum of the heights of the washes made by the two ships independently. The second possibility is that, as there have been found to be restrictions on the amount of deformation associated with the two separate world-lines, there may be a further restriction on the deformation arising from their combination.

In actual fact the former alternative appears to prevail when one or both of the charged particles are "free" electrons, but the latter alternative when they are "bound" together; that is, when they are permanently describing orbits about one another. It is these latter restrictions that have given rise to the

theory of quanta. Just as the restrictions associated with single world-lines give rise to an atomic constant e, the charge on an electron, so the restrictions associated with pairs of world-lines give rise to a second atomic constant. This is generally taken to be h, Planck's constant, but in many respects it is more appropriate to regard the product hc as the second constant, where c is the velocity of light. It is significant that hc is of the same physical dimensions as e^2 and so may be regarded as being the same thing as e^2 except for a numerical multiplier. Thus while the restrictions connected with one world-line introduce e, those connected with two world-lines, depending only on e^2, introduce no essentially new constant, whence it may reasonably be suspected that the two sets of restrictions are merely different aspects of one and the same set. It looks as though the atomicity of the quantum theory is only another aspect of the atomicity of electric charges.

Quantum-Restrictions.

We can perhaps best visualize the inner nature of the quantum-restrictions by going back to the analogy of the two ships making a combined wash which is in some way restricted to being of a certain height. We have supposed each wash individually to be restricted; if the velocity of the ships is fixed, this requires that each ship shall be of a definite size (corresponding to each electron having a definite charge). How can we now put a further restriction on the total wash of the two ships at points where their washes overlap? Only, I think, by keeping the ships at a specified distance apart. At any rate this is the way in which the quantum-restrictions work. The normal hydrogen atom consists of a negative electron describing a circular orbit about a positively charged nucleus; the quantum-restrictions compel this orbit to keep an unvarying radius of $0 \cdot 53 \times 10^{-8}$ cm. When the atom is in an abnormal state, as, for example, when excited in a vacuum tube, the orbit, if circular, may have radii equal to 4, 9, 16, 25 . . . times the radius of the normal atom. Elliptic orbits also are possible, but only of quite definitely restricted major and minor axes. In actual fact the semi-major axis must be equal to one of the radii permissible for a circular orbit, while the ratio of the two axes must be one of a range of commensurable ratios. The orbits which are possible for the electron of the hydrogen atom are shown in Fig. 2. If it were not for the quantum-restrictions, it would be impossible to exhibit these orbits in a diagram at all; orbits of every radius and of every eccentricity would be possible, just as they are for a planet or comet describing an orbit about the sun.

It will be understood that I have not approached the quantum theory by the road of its historical development. Planck originally discovered the existence of the quantum-constant h from a study of black-body radiation. The famous theorem of equipartition of energy showed that if the classical laws of dynamics were of universal validity, the whole energy of the material universe would at once degrade itself into radiant energy of infinitesimal wave-length. Planck showed that this conclusion could be avoided by supposing that the energy of radiating mechanisms changed only by complete quanta, the change of energy $W_2 - W_1$ being connected with the frequency ν of the radiator by the relation

$$W_2 - W_1 = h\nu$$

He further showed that this supposition led to a law of spectral distribution of black-body radiation, the now famous Planck's law, which was found to agree excellently with the observed distribution. In this way the quantum theory came into being at the very beginning of the quarter-century we have under review.

Some years elapsed before Einstein showed that the same constant was of fundamental importance in the photo-electric effect, and it then began to be suspected that it might conceivably be fundamental to the whole of physics. But it was not until 1913 that Bohr published the epoch-making paper which first suggested, and at the same time finally established, that this constant held the clue to the structure of the atom and determined the scale on which the universe

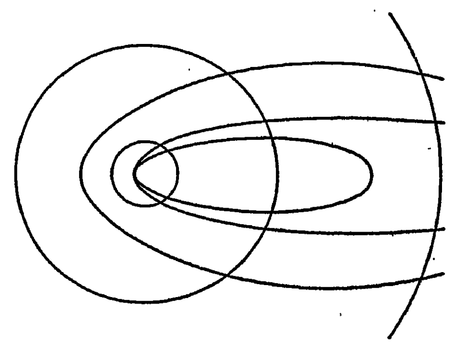

Fig 2.

is built. To-night I have disregarded historical development altogether, and have tried to approach the theory in the simplest manner; I am trying to make it look natural. There can be no reasonable doubt that the quantum theory is essentially true and so would appear perfectly natural to us if we could approach it with entirely fresh minds not already obsessed by erroneous ideas. But with our minds such as they are, the quantum theory as frequently presented does, it must be admitted, raise recollections of plausible conjuring performances. If I were to state the argument by which Planck first arrived at the existence of the quantum, the inclination might well be to dismiss it as mere mathematical sleight-of-hand. I agree it is still a bit surprising that the rabbit came out of the hat, but I have tried to show at least that there was so much room in the hat that almost anything might have emerged.

According to the Maxwellian electrodynamics an electron describing an orbit of any kind must necessarily radiate energy. We can calculate the rate at which energy ought to be radiated by the electron in the normal hydrogen atom; it is $0 \cdot 46$ erg a second. The resulting loss of energy would be compensated by a decrease in the radius of the orbit; we find that the

rate of this decrease would be about 112 cm a second, so that the atom ought to disappear altogether within a small fraction of a millionth of a second. Thus it is the quantum-restrictions which give a permanent existence to matter.

In conformity with the quantum-restrictions, the electron in the hydrogen atom describes an orbit of unvarying radius and so of constant energy. Maxwell's equations, as we have seen, would demand that radiation should be emitted and that the energy of the orbit should decrease accordingly. Here, then, we have a case where the requirements of Maxwell's theory and those of the quantum theory are in irreconcilable conflict. It is the quantum theory which carries the day. Somewhere before we reach the most minute of all structures Maxwell's theory fails and the quantum theory takes its place. For large-scale phenomena the two theories coincide—a thunderstorm is the same thing for Maxwell's theory as for the quantum theory, just as it was the same thing for the old "one-fluid" theory as for the modern electron theory—atomicity is of no consequence when the number of atoms involved approximates to infinity.

In terms of space curvatures we may say that Maxwell's theory is represented by a continuous curvature or crumpling such as might be applied to a rubber membrane, while possibly the quantum theory may be represented by a so-to-speak "jerky" deformation which is the best that can be done with a scaly surface such as a crocodile skin. If we wish to cover the earth's surface with a membrane, it makes little difference, from the point of view of closeness of fit, whether we select rubber membrane or crocodile skin, but it makes all the difference if we are manufacturing a pair of gloves. The quantum theory represents, perhaps, a quality of space, or rather of the four-dimensional continuum, which is somehow analogous to scaliness in a skin.

As the normal hydrogen atom is already in its configuration of minimum energy it can emit no radiation. But under electric bombardment or in the presence of intense radiation the electron may move to other orbits of energy higher than the minimum. Even now there can be no gradual change of energy, but there can be spasmodic jumps from one orbit to another orbit of lower energy. According to Bohr's theory of atomic mechanism, the energy lost to the orbit at each end of these jumps is emitted in the form of monochromatic radiation. A jump from energy W_2 to energy W_1 results in the emission of radiation of uniform frequency ν where

$$W_2 - W_1 = h\nu$$

h being the absolute constant of Nature already referred to. If λ is the wave-length of the radiation, $\lambda = c/\nu$, so that

$$W_2 - W_1 = \frac{hc}{\lambda}$$

We have already seen that hc is equal to Ke^2, where K is a numerical constant. The energy in an orbit of radius r (or, if elliptical, of semi-major axis r) is $\frac{1}{2}e^2/r$, so that if the jump is from an orbit of radius r_1 to one of radius r_2,

$$\tfrac{1}{2}e^2\left(\frac{1}{r_2} - \frac{1}{r_1}\right) = \frac{Ke^2}{\lambda}$$

and the wave-length of the radiation is given by

$$\frac{2K}{\lambda} = \frac{1}{r_2} - \frac{1}{r_1}$$

Now if a is the radius of the normal hydrogen atom, the possible values for r_2 and r_1 are $1^2, 2^2, 3^2, 4^2 \ldots$ times a, so that our formula becomes

$$\frac{2Ka}{\lambda} = \frac{1}{n_2^2} - \frac{1}{n_1^2}$$

In actual fact a formula of this type, in which n_1 and n_2 are given all possible integral values, is found to give with the utmost exactness the wave-lengths of the light emitted in the complicated spectrum of the hydrogen atom. On putting $n_2 = 2$ we obtain the Balmer series of lines, of which the principal lines H_α, H_β, $H_\gamma \ldots$ form the most conspicuous feature in the ordinary hydrogen spectrum. The lines obtained by putting $n_2 = 1, 3, 4, 5 \ldots$ are mostly in the infra-red or the ultra-violet. Many of these have been observed, and there is no reason to doubt that the remainder are there, although at present beyond the range of observation.

So far we have considered only the circular orbits; there must, of course, be other spectral lines arising out of the possibility of the electron describing elliptic orbits. Exact analysis shows, however, that these latter lines coincide almost exactly with those already discussed. They would coincide perfectly if it were not that the mass of a moving electron depends on the velocity of its motion. As a consequence of this dependence of mass on velocity, the two sets of lines do not exactly coincide. Each line of the simple series previously discussed is replaced by a "fine-structure"—a bunch of lines quite distinct in fact, although so close together as to look like a single line in all save the most powerful spectroscopes. Sommerfeld has worked out the structure to be expected theoretically for these bundles of lines and obtains a most gratifying agreement with observation. This and other experimental tests give the most convincing proof of the accuracy of Bohr's theories of atomic mechanism.

We can gain a knowledge of the arrangements of the electron orbits in even the most complicated atoms by using the equation

$$W_2 - W_1 = h\nu$$

which appears to be of universal validity. The frequencies ν of radiation can be measured, so that the energy-levels W_1, $W_2 \ldots$ of the various possible orbits can be calculated. The method has been applied not only to discovering the arrangements of electrons in the atom, but also to discovering the energy-levels of the protons in the nucleus. At present the hydrogen atom and the positively-charged helium atom are the only structures which are completely understood, but there can be little doubt that in time the method will unravel for us the secrets of even the most complicated of atomic and molecular structures.

Already Bohr has constructed a table, of which the first part is shown in Table 1, in which he attempts to

TABLE 1.

Electron Orbits.

		1_1	2_1	2_2	3_1	3_2	3_3
1	H	1					
2	He	2					
3	Li	2	1				
4	Be	2	2				
5	B	2	2	(1)			
10	Ne	2	4	4			
11	Na	2	4	4	1		
12	Mg	2	4	4	2		
13	Al	2	4	4	2	1	
18	A	2	4	4	4	4	

assign the different electrons in the atoms to the various orbits permitted to them by the quantum theory. The numbers in the top line specify the orbits in terms of their principal and subsidiary quantum numbers. The numbers below are the numbers of electrons which follow one another round in these different orbits. It will be noticed that in the simpler elements there are never more than four electrons in the same orbit, although in the heavier elements six and afterwards eight electrons may inhabit the same orbit. The table is largely conjectural, but recent spectroscopic research has gone far towards establishing its essential accuracy. When we remember that it is less than twelve years since Bohr first suggested that the quantum theory might provide the clue to the structure of matter, we must agree that the progress of the theory in these years has been remarkable.

THE NATURE OF RADIATION.

The quantum theory has been less successful in discovering the nature of radiation, although even here it has been beyond comparison more successful than any previous theory. To illustrate the difficulties of the problem, let us consider one single phenomenon—the X-ray photo-electric effect. A thin stream of electrons each moving with the same high velocity is allowed to impinge on a material target, and X-rays are emitted which carry off the energy destroyed by the collision. These X-rays pass through a gas, and it is found that as soon as the process starts, atoms are ionized and shoot off electrons with a velocity equal to that of the original stream of electrons. Even if the density of X-radiation is so slight that, according to the old view of radiation, an atom would take years to absorb the energy necessary for ionization, nevertheless ionization is found to begin at once, energy being absorbed which is not only sufficient for mere ionization, but also suffices in addition to endow the ejected electron with high velocity.

Such a phenomenon is of course totally inexplicable in terms of the luminiferous ether, or even in terms of Maxwell's equations. The quantum theory gives only a partial explanation. Since the frequency ν of the X-rays does not change with their passage through space, the equation $W_2 - W_1 = h\nu$ shows that the change of energy at the one end of the chain must be equal to that at the other. Thus as much energy is necessarily yielded up to one electron as is destroyed in another, but this does not touch the problem of the mechanism by which this energy is transferred.

Einstein at one time suggested that radiant energy was hurled through space tied up in indivisible packets like bullets from a rifle, but it has proved quite impossible to reconcile this suggestion with the optical phenomena of interference. A more recent hypothesis, also due to Einstein, calls for a revision of our conception of the action of an electric field on an electron.

According to the usual electrical theory an electric force X acting on an electron of charge e and mass m for a time t produces a change of velocity equal to Xet/m. According to Einstein's recent theory of radiation, this is only true if X arises from a steady field or from a field which changes infinitely slowly. A force X which results from the incidence of radiation will in general produce no change of velocity at all in an electron. Indeed a bound electron is compelled to describe a fixed orbit with a prescribed velocity which cannot change, while a quite simple argument shows that it would be contrary to the fundamental equation of the quantum theory for a free electron to have its velocity changed by radiation. Einstein, following Bohr, supposes that under certain conditions a bound electron can have its velocity changed by a definite amount Q. This amount is not equal to Xet/m, but is determined by the position and motion of the electron in the atom to which it belongs; Q must be such as to move the electron into a new orbit which is also one of the permitted few. The chance of such a jump of velocity occurring is supposed to be

$$\frac{(Xet/m)}{Q}.$$

This conception immediately explains the otherwise incomprehensible photo-electric effect as well as other puzzles in the behaviour of radiation. The difference between a strong and a weak electric field acting on an electron is no longer that the strong field produces a big change of velocity and the weak field a small one; it is that the strong field has a big chance of producing a change, and the weak field only a small chance of producing the same change. When radiation acts on a body containing a great number of electrons the final result is the same on the new theory as on the old. But there is a difference of method which is similar to the difference in propulsion between a motor-car and a steam engine; on the new theory the charged body is propelled by a succession of little kicks, whereas on the old theory it was propelled by a steady pressure.

I have tried to sketch, in the short time at my disposal, the outlines of the changes which the past quarter-century has introduced into our conception of the nature of electric forces and of the electromagnetic field. You will agree with me that there have been giants at work in the field of pure electrical theory. When the history of present-day science comes to be finally written, the quarter-century we have just lived through will, so far as we can now judge, stand out as the period in which man first began to understand the true nature of electricity.

ANNUAL DINNER, 1925.

The Annual Dinner of the Institution was held on Thursday, 12th February, 1925, at the Hotel Cecil, when the President, Mr. W. B. Woodhouse, presided over a gathering numbering 522 persons.

Among those present were: The Rt. Hon. Sir A. Steel-Maitland, Bart., M.P. (*Minister of Labour*), Lt.-Col. the Rt. Hon. Wilfrid Ashley, M.P. (*Minister of Transport*), The Rt. Hon. the Viscount Falmouth (*Member of Council*), The Rt. Hon. Sir Henry Norman, Bart., P.C., The Hon. Sir Charles A. Parsons, K.C.B., F.R.S. (*Hon. Member and Faraday Medallist, I.E.E.; President, Institute of Physics*), The Rt. Hon. Sir J. Cook, G.C.M.G. (*High Commissioner for the Commonwealth of Australia*), The Hon. Sir T. Mackenzie, G.C.M.G., M.L.C. (*New Zealand*), The Hon. Sir T. A. Coghlan, K.C.M.G., I.S.O. (*Agent-General for New South Wales*), Sir M. Sheldon, K.B.E. (*New South Wales*), The Hon. H. P. Colebatch, C.M.G. (*Agent-General for Western Australia*), The Hon. J. Huxham (*Agent-General for Queensland*), Sir Sydney Chapman, K.C.B., C.B.E. (*Permanent Secretary, Board of Trade*), Sir Frank Heath, K.C.B. (*Secretary, Department of Scientific and Industrial Research*), Sir James Devonshire, K.B.E. (*Vice-President*), Sir Joseph E. Petavel, K.B.E., D.Sc., F.R.S. (*Director, National Physical Laboratory*), Sir Charles Bright, F.R.S.E., Sir Tom Callender, Sir Arthur Durrant, C.B.E., M.V.O. (*H.M. Office of Works*), Sir Henry Mance, C.I.E. (*Past President*), Sir William Noble, Sir John Snell (*Past President, I.E.E.; Chairman, Electricity Commission*), Rear-Admiral C. T. M. Fuller, C.B., C.M.G., D.S.O. (*Third Sea Lord and Controller of the Admiralty*), Colonel G. H. Addison, C.M.G., D.S.O., R.E., Mr. T. H. U. Aldridge (*Chairman, China Centre*), Mr. P. F. Allan (*Hon. Secretary, North-Eastern Centre*), Mr. Ll. B. Atkinson (*Past President, I.E.E.; Chairman, British Electrical and Allied Industries Research Association*), Major R. L. Barclay, C.B.E. (*Chairman of Council, London Chamber of Commerce*), Mr. J. W. Beauchamp (*Member of Council*), Mr. H. Booth, O.B.E. (*Electricity Commissioner*), Mr. J. R. Brooke, C.B. (*Permanent Secretary, Ministry of Transport*), Mr. A. Carpmael, B.A., Mr. R. A. Chattock (*Member of Council*), Mr. F. W. Crawter (*Member of Council*), Colonel R. E. Crompton, C.B. (*Past President and Hon. Member*), Mr. J. Dalton (*Master, Drapers' Company*), Mr. R. A. Dalzell, C.B., C.B.E. (*Director of Telegraphs and Telephones, G.P.O.*), Mr. W. R. Davies, C.B. (*Principal Assistant Secretary, Technical Branch, Board of Education*), Mr. J. Duncan-Hughes (*Member of House of Representatives, South Australia*), Mr. D. N. Dunlop (*Member of Council*), Dr. W. H. Eccles, F.R.S., Lt.-Col. K. Edgcumbe (*Member of Council*), Dr. S. Z. de Ferranti (*Past President and Faraday Medallist*), Mr. F. Gill (*Past President*), Monsieur J. Grosselin (*Past President, Société Française des Electriciens; I.E.E. Local Hon. Secretary for France*), Mr. A. F. Harmer (*Member of Council*), Mr. H. H. Harrison [*Chairman, Mersey and North Wales (Liverpool) Centre*], Mr. H. Hastings (*Local Hon. Secretary for Spain*), Mr. W. C. Henderson, K.C., D.Sc., Mr. J. S. Highfield (*Past President*), Mr. W. E. Highfield (*Member of Council*), Mr. H. Hooper (*Hon. Secretary, South Midland Centre*), Mr. G. W. Humphreys, C.B.E. (*Chief Engineer, London County Council*), Dr. H. H. Jeffcott (*Secretary, Institution of Civil Engineers*), Mr. T. B. Johnson (*Chairman, North Midland Centre*), Mr. W. E. Tyldesley Jones, K.C., Mr. G. A. Juhlin (*Past Chairman, North-Western Centre*), Mr. J. E. Kingsbury, Mr. W. W. Lackie, C.B.E. (*Electricity Commissioner*), Mr. W. Lawson (*Chairman, South Midland Centre*), Mr. S. R. Lowcock (*Chairman, Association of Consulting Engineers*), Mr. W. McClelland, C.B., O.B.E., Captain L. McNamee, U.S.N. (*Naval Attaché, United States Embassy*), Mr. Stanley Machin, J.P. (*President, Association of British Chambers of Commerce*), Brig.-Gen. H. O. Mance, C.B., C.M.G., D.S.O., Mr. S. W. Melsom (*Member of Council*), Mr. H. M. Morgans, B.Sc. (*President, Institution of Mining and Metallurgy*), Brig.-General M. Mowat, C.B.E. (*Secretary, Institution of Mechanical Engineers*), Mr. W. Nairn (*Chairman, Western Centre*), Mr. W. H. Norton (*President, Incorporated Law Society*), Mr. A. Page (*Vice-President, I.E.E.; Electricity Commissioner*), Mr. F. Palmer, C.I.E. (*Past President, Institution of Civil Engineers*), Mr. C. C. Paterson, O.B.E., Mr. L. St. L. Pendred (*Member of Council, Institution of Mechanical Engineers*), Col. T. F. Purves, O.B.E. (*Member of Council, I.E.E.; Engineer-in-Chief, G.P.O.*), Mr. P. J. Pybus, C.B.E., Mr. W. R. Rawlings (*Member of Council*), Dr. Alexander Russell, M.A., LL.D., F.R.S. (*Past President*), Mr. E. H. Shaughnessy, O.B.E. (*Member of Council*), Mr. Roger T. Smith (*Past President*), Mr. C. P. Sparks, C.B.E. (*Past President*), Colonel H. C. Sparks, C.M.G., D.S.O., M.C., Mr. A. A. Campbell Swinton, F.R.S. (*Vice-President*), Mr. W. C. P. Tapper (*President, Incorporated Municipal Electrical Association*), Captain T. Toyoda, D.S.O., I.J.N., Mr. P. D. Tuckett (*Hon. Treasurer*), Mr. O. C. Waygood [*Hon. Secretary, Mersey and North Wales (Liverpool) Centre*], Mr. W. J. U. Woolcock (*President, Society of Chemical Industry*), and Mr. P. F. Rowell (*Secretary*).

After the Loyal Toasts had been duly honoured, the President read the following messages from other Societies :—

From the Société Française des Electriciens :—

"Heartily congratulate the Institution of Electrical Engineers on the magnificent example of development and fruitful activity which it gives to all sister societies. The French Society looks forward with pleasure to the opportunity for close collaboration which will be provided by the conference on High Tension Lines to be held in Paris next June."

From the Associazione Elettrotechnica Italiana :—

"While thanking you and the Council for the kind invitation to the Annual Dinner of your great Institution,

I much regret my unavoidable absence. At the same time I take the opportunity of presenting my deepest respects to you and of expressing to the Institution the deepest gratitude of the Italian Electrotechnical Association for the kindness shown to us in London last July. GIUSEPPE SARTORI, President."

The Rt. Hon. Sir Arthur Steel-Maitland, Bart., M.P. (Minister of Labour), in proposing the toast of "The Institution of Electrical Engineers," said: "I am deeply sensible of the honour of being asked to propose this toast. From one point of view it is quite superfluous to propose the Institution's health, because the vitality of the Institution is amply shown by the figures of its membership. There is, however, a greater significance in its growth than is indicated merely by its numerical well-being. It is my business—and not always a pleasant one—to look over the state of industry and employment throughout the country, and I find that unemployment in the electrical industry is much less than one-half of what it is in the insured trades of the country as a whole. I should be far from saying that this means that it is all plain sailing in the industry. If there is a margin of profit in the business it is very often not a great one, and I know that sometimes it does not exist at all. All the same, I do see in the electrical industry the expansion of exports—not rapid, but, still, steady—and the industry at home growing in volume though I am bound to say that I wish we could supply all the home requirements without assistance from abroad. Therefore, I always think that although the fortunes of other engineering trades are alternating, the electrical industry has got a quite direct current towards success, and truly the importance of such an expansion goes beyond the Institution and beyond the industry itself. It is over a century since this country knew anything like the depression in trade from which we have suffered here during the last four years. After the Napoleonic wars there was something akin to it, but only then; and in that day the cure came through the general manufacturing expansion that took place over the country as a whole. To-day there is no such possibility of great general expansion, but the electrical is the one industry in which there is a great and immediate and quite inevitable growth, and to my mind it is to the expansion in electricity, both in itself and in the facilities which it can provide to other industries in town and country, that we have got to look for the large improvement which we hope will take place in the existing conditions in England and Scotland to-day. In the electrical industry it always seems to me that, while it is true of all other industries that technical skill and organizing capacity are needed, there is a special need in electricity as in chemistry to use every means available for keeping up with and, if possible, getting in front of the other great competing countries. When I was in charge of the Department of Overseas Trade it always seemed to me that neither America nor Germany took any account of the electrical industry of our country when they set to work to divide up the world's markets. Broadly speaking, that was the case before the war, but during the war, and since, there has been a development here in the electrical world that has made other great countries take account of us as one of themselves before they proceed to divide up the trade of the world. It is, however, absolutely vital to us to keep abreast of them in technical skill and organization, and in an open-minded view of the whole situation, so that the development of electricity may work out to the benefit of the country as a whole. If these vital considerations are to be fulfilled they have got to be fulfilled by the Institution of Electrical Engineers. It is for that reason that, speaking as a business man to men of business and of science, I venture to wish in absolute sincerity all prosperity to the Institution and I am proud to propose its health this evening."

The President, in responding, said: "I must thank the proposer of the toast for the good wishes which he has expressed in regard to the Institution. The Institution is indeed growing rapidly, and its growth is, I think, an indication of the growing importance of electrical engineering in civilization to-day. We are living in a period of the most extraordinary scientific activity, when not merely are many of the fundamental theories of physics being upset and replaced by new ones, but almost it seems that every worker in the field of science is bound to discover some new result which can be applied at once by the engineers, and in practically all such applications electricity takes a part. That is not to be wondered at, I suppose, if one accepts the modern theory that electricity is more fundamental than matter. It must, however, make electrical engineers think not only of the immediate future, but of the enormous possibilities of development which are taking place and the enormous changes in scientific applications which must ultimately be brought about. The period in some respects reminds one of the latter part of the eighteenth century when the steam engine was being created and when every day the application of this new power led to some new discovery and some new development. In making that comparison I do not think that the position of the electrical engineer to-day can be more aptly described than in the remark that Matthew Bolton made to Boswell some 150 years ago when Boswell visited his works at Soho, two miles from Birmingham: 'I sell here, Sir, what all the world desires to have—POWER.' I think that is the keynote of the electrical engineer's work to-day.

"The transmission of messages by electrical means has brought about a closer association of mankind of the utmost value. It is only a very short time since one of our Past Presidents, Mr. F. Gill, told us of his dream of international telephony. That dream to-day seems as if it is going to be realized, and the work of electrical engineers in all civilized countries will by that means have a tremendous effect on their development. Broadcasting has become world-wide. We hear of telephone messages being received in the most distant parts of the earth, and the future possibility of vocal communication with our kinsmen in all the Dominions of the Empire is a consideration that one must welcome; communication between the far-off Dominions and this country by means of direct speech will be a change from our present method of communication which must bring about the closer and closer association of the English-speaking races.

"In the field of manufacture electrical engineers, in a time of national trade depression, have, relatively speaking, been prosperous. No doubt our manufacturers have to complain of high taxation. No doubt they have to complain also of the diminished power of foreign countries to purchase our products. But, as Sir Arthur Steel-Maitland has pointed out, we have a great deal for which to be thankful, as compared with the general engineering trade. Whatever deficiency there may be in our export trade, I think it will be agreed that it is not due to any deficiency of ability or energy on the part of the electrical manufacturers of this country. The wonderful exhibition of British engineering at Wembley last summer was a demonstration to the world that we have in no way lost our ability to produce the finest machinery in the world; and I have no doubt that the effect of that Exhibition will be far-reaching and will, in course of time, as other countries acquire the means of purchasing, have its effect on our export trade. As to the home market for our manufactures, perhaps the electricity supply industry is the best index of what that market is and may be, and I think one may safely say that the prospect there is rosy. The public supply of electricity is a very great power for increasing the comfort of the people, for improving health, and for the reduction of arduous labour—all of which must have an effect not only on the prosperity of the country, but on the happiness of the people. The use of electricity in the home is developing so rapidly that it seems to me that in a very few years the tasks of domestic labour will be reduced out of all knowledge, so much so, that one may perhaps look forward to the day when a candidate for Parliament need only say that he is an electrical engineer to receive the solid support of the women voters! The electricity supply industry, although in the past it has suffered very much from legislation, is now booming, and it will continue to do so, I think, if it is given a fair field. There is a considerable amount of public misunderstanding as to the progress that has been made in electricity supply in this country both during and since the war. In fact, only to-day I saw a statement in a newspaper that the average price of electricity in this country was 5d. a unit. It is hardly necessary to mention that that is erroneous. The average price at which the power companies in this country have been selling electricity is less than 1d. per unit, whilst the big municipalities, despite the larger proportion of lighting with which they have to deal, have sold current at an average price not much higher than that of the power companies. It only needs a continuation of the present development and demand for electricity to ensure that in a few years even these prices will be substantially reduced. To attain this the industry needs freedom from disturbance, or at least, if any change is proposed, an assurance that the views of the industry will be taken before any final plans are made. I think I can say on behalf of the members that the Institution will be only too glad to give its assistance in any matter of that kind. Whatever difference of opinion there may be as to electrical legislation, I think there is no doubt that we are all of one opinion as to the able way in which the laws governing electricity supply have been administered, and I should like to take this opportunity of expressing the widespread regret at the forthcoming retirement of one of the Electricity Commissioners, Mr. Harry Booth. Finally, as to the Institution, I think that the position of the electrical engineer to-day, and the position of the Institution also, are due very largely to that happy spirit of co-operation, that willingness to exchange information and that ability to work together for the good of science and industry which all engineers seem to possess. I believe that the Institution will continue to work for the development of science, for research, for invention, and for knowledge, not only in the interests of the profession of electrical engineers, but in the interests of our country and of the great Empire of which it is a part."

Sir John Snell (Past President, I.E.E., and Chairman, Electricity Commission) then proposed the toast of "Our Guests," to which **Lt.-Col. the Rt. Hon. Wilfrid Ashley, M.P.** (Minister of Transport), and **The Rt. Hon. Sir Joseph Cook, G.C.M.G.** (High Commissioner for the Commonwealth of Australia), responded.

A reunion was subsequently held in the Victoria Hall of the hotel.

THE OPTIMUM DAMPING IN THE AUDITIVE RECEPTION OF WIRELESS TELEGRAPH SIGNALS.

By L. B. Turner, M.A., Member, and F. P. Best, M.Sc., Student.

(*Paper received 3rd October, 1924, and read before the* Wireless Section *4th February*, 1925.)

Summary.

This paper is an account of an experimental investigation of the extent to which it is advantageous to reduce the damping in a receiver for telegraphic signals from modern continuous-wave stations, when the usual rectifier and telephone are used as indicator. It was found possible to produce, hold stable, and measure decrements below those giving optimum reception. Numerous determinations of optimum damping were made, the observed signals coming from six commercial transmitting stations of wave-lengths ranging from about 4 000 to 23 000 m. The several observations on any one station show remarkable accord amongst themselves, and the measured optimum damping exponents for all stations and wave-lengths are found to lie within a narrow range. The significances of speed of signalling in relay and in auditive reception are contrasted.

Table of Contents.

(1) Introduction.

It was pointed out in a recent paper * by one of the present authors that in the modern wireless technique it is feasible to employ receiving circuits in which the damping is reduced, by triode retroaction, further than it is advantageous to go. As the decrement of the receiving circuit is reduced, its response to a sustained tuned incoming signal is augmented, but therewith the inertia effects, which are responsible for the transient epochs following the starting and stopping of the incoming signal, become more and more pronounced. Sensibly "square-topped" signal E.M.F.'s impressed on the receiver by the sending station produce in the receiver "saw-tooth" current curves, resembling the "arrival curves" of a submarine telegraph cable, the shape of the curves being determined by the product $n\delta T$, where n is the frequency of the signal E.M.F., δ is the decrement of the receiving circuit, and T is the duration of the signal element (the morse dot). In the paper referred to, arrival curves were calculated for various values of $n\delta T$, with the specific object of estimating theoretically how small $n\delta T$ can advantageously be made when a relay is used to record the signals. A limiting value of $n\delta T$ in the neighbourhood of 2 is there suggested; this would make $n\delta = 200$ for a speed of 125 words per minute (w.p.m.), and $n\delta = 40$ for 25 w.p.m.

It might at first be thought that the results of this theoretical examination of relay reception could be applied to the ordinary auditive reception by rectifier and telephone, and that accordingly $n\delta = 40$ would be about the most propitious value of the damping index in such a receiver, since aural speeds are around 25 w.p.m. Any experimental test of such an hypothesis would of course be very valuable. But in truth the question is complicated by psychological considerations; and experience seems to indicate that the ear, when reading weak morse signals, is unable to tolerate too gradual a rise and fall of sound at the beginning and end of the morse dot or dash, however much protracted may be the sensibly uniform sound intervening. Expressed otherwise, the ear, unlike a relay, seems to demand adequate definition of the beginning and end of a mark, however low the rate of signalling. Consequently, although the operator of a suitable receiver may have complete control of the damping (and can indeed cause it to pass through zero, so that his receiving circuits generate oscillations), there must be some most propitious setting. This setting is probably more or less independent of the speed of signalling, provided the latter is low. He is able to reach it by trial, his ear being the guide; but what the damping of the receiver may then be appears to have been hitherto merely conjectural. We know of no data, before the present experiments, for making the definite calculation in any particular case, or even for framing a rough theoretical estimate.

The experimental investigation * described here had for its aim the determination of optimum receiver dampings for continuous-wave morse signals under practical working conditions. The signals observed were the ordinary signals issuing from various intercontinental stations at work on wave-lengths between 4 350 and 23 450 m; the receiver, with independent heterodyne, contained an oscillatory circuit of very low damping, the tuning and damping being under perfect control; and the adjustments were effected under guidance of the ear of the observer to make the resulting signals most easily *legible* when they were so reduced as to be only very faintly *audible* in the telephones. The decrement of the circuit thus adjusted is termed the optimum decrement for that incoming signal, and

* L. B. Turner: "The Relations between Damping and Speed in Wireless Reception," *Journal I.E.E.*, 1924, vol. 62, p. 192.

* The work was carried out in the wireless laboratory of the Engineering Laboratory, Cambridge University, with the permission of Prof. C. E. Inglis during 1922–23.

was thereupon measured. The chief experimental difficulty to be met was to ensure that the decrement during the measuring operations remained at the value given to it during the adjusting (receiving) operation; for the low decrements involved—down to 0·002—could be obtained only by resort to triode retroaction, and the value of negative resistance introduced by retroaction is of course subject to alteration with alterations of oscillation amplitude occurring in the process of measurement.

Our ignorance of the actual values of such receiver decrements seemed so profound that if results could only have been obtained subject to wide errors—say between twice and one-half the true value—the work would have been regarded as fruitful; and since the adjustment depended upon a psychological judgment of the optimum, it was expected that some such divergences would have been recorded, at least as between two observers, even if not so markedly with a single observer. Experience has shown, however, that the concordance between several independent adjustments and measurements on the same station is very much better than had been anticipated, the optimum degree of "ringing" of the signals as adjusted by two observers, or by one observer on different days, showing decrements of remarkable uniformity.*

(2) Experimental Method.

The circuits adopted are shown in skeleton in Fig. 1. The low-decrement circuit under test is C_1L_1. It forms part of the anode circuit of triode 2, and is excited by the signal applied to the grid of triode 2 from an aperiodic aerial circuit via an aperiodic amplifier triode 1. A powerful local heterodyne oscillator is very loosely coupled to L_1 by L_4. This oscillator serves as heterodyne when adjusting the receiver for the signals, and as the exciting circuit when the decrement of the receiver is subsequently measured. The amplitude of oscillation in C_1L_1 is observed by a Moullin voltmeter M.V.† placed across the anode circuit ‡ of an amplifier triode 3, which also excites the amplifier-rectifier 4. The anode circuit of triode 4 contains the retroaction coil L_3 very loosely coupled to L_1, serving to reduce the decrement of the C_1L_1 circuit to any desired value; also the telephone T for observing the signals when adjusting the retroaction. These circuits were arrived at after much preliminary work, and a brief explanation of their features is given.

The introduction of the amplifier triode 3 permits a very loose coupling between coils L_1 and L_3, so that wide mechanical movement of L_3 with respect to L_1 is required for small variations of retroaction, and the decrement of the circuit C_1L_1 is controlled with great precision.

In order to avoid all question of alteration of damping under the action of the signal itself, it is essential that the amplitude of signal used in adjusting for the optimum decrement should be extremely small. Further, the additional deflection of M.V. produced by the incoming signal must be negligible in comparison with the deflection already produced by the heterodyne alone, since otherwise the kick of the instrument would prevent an accurate reading. On this account, and in order that the coupling between L_1 and L_4 should be very small, an unusually powerful heterodyne oscillator was used.

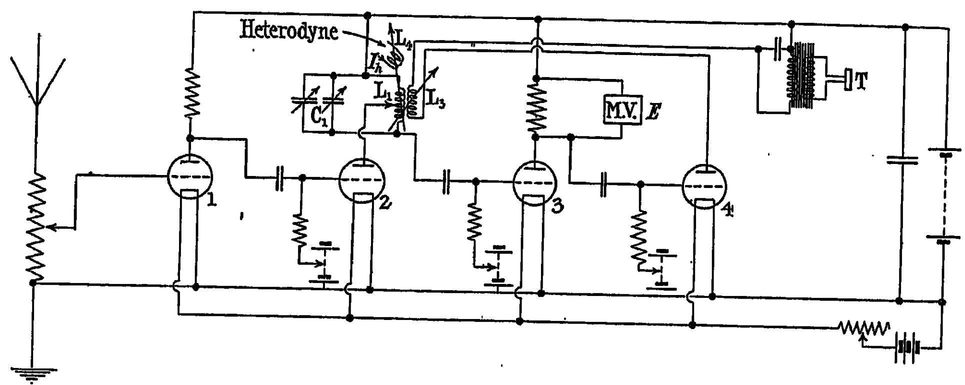

Fig. 1.—Circuit used in the tests.

The use of the heterodyne oscillator itself, with no displacement of the coupling coil L_4, for the subsequent measurement of the decrement is regarded as an important feature. With the very low decrements involved, a separate oscillator for measuring the decrement could hardly be introduced without endangering the constancy of the decrement.

It had seemed likely that, for reception of the American stations, it would be necessary to use an amplifier triode 1 between the aerial and the low-decrement circuit C_1L_1. This amplifier was later found to be unnecessary, but was retained as being quite innocuous.*

To avoid grid current damping in triode 3, which if present would necessarily vary with oscillation amplitude, a high anode potential was used, with considerable negative bias on the grid. The value of grid potential

* An observer whose assistance was requested was always asked to adjust until the signal became most legible in his own judgment.

† See *Journal I.E.E.*, 1923, vol. 61, p. 295.

‡ Shown here as a resistance, but actually a relatively highly damped oscillatory circuit, of which more will be said hereafter.

* The aerial used was some 90 ft. high at one end. Usually only a very small fraction of the available P.D. was tapped off from the aerial circuit potentiometer.

in each of the triodes 1, 2 and 3 was capable of separate adjustment, and before any measurements were made the grid potential was adjusted so that the triode was operating at about the middle of the nearly straight portion of its characteristic. Alterations of triode parameters consequent on minute unavoidable changes of amplitude while setting the receiver and measuring the decrement were thereby reduced to a minimum.

After the receiver has been adjusted, the decrement must be measured without making any change liable to alter that decrement. Consequently the amplitude in C_1L_1 must not be appreciably altered, a proviso which rules out the usual methods of determining the decrement of a circuit by observing change of amplitude therein consequent on a known alteration of its resistance or reactance (distuning). Further, even though L_3 and L_4 are but very lightly coupled to L_1, no movement of those coils should be made. These conditions led to the following rather elaborate ritual—viz. operations (*a*), (*b*), (*c*) and (*d*) described below—which was practised at each observation.

Operation (*a*). *Setting the receiver.*—Tune C_1L_1 to the signal, and tune the heterodyne to give a high-pitched note therewith. Increase the retroactive coupling L_1L_3, so strengthening the signal and increasing the sharpness of tuning of C_1L_1; and maintain the weakness of signal by lowering the tapping point on the aerial potentiometer. Adjust coupling L_1L_4 and (if necessary) the heterodyne current I_h in L_4, so that M.V. reads a value E between 1 and 2 volts.* Proceed with these adjustments and readjustments, taking special care to leave C_1L_1 exactly tuned to the signal, until the retroaction is judged to be that enabling limitingly weak signals to be most easily read. There is then a certain amount of "ringing" (merging of marks and spaces), any increase of which would more than offset the accompanying gain of strength. The damping of C_1L_1 is now of the "optimum" value; we have still to measure it.

Measuring the decrement.—The method is to impress in C_1L_1 two E.M.F.'s of slightly different frequencies and suitably different amplitudes such that the current amplitude in C_1L_1 remains at precisely the value given by operation (*a*). These E.M.F.'s are impressed from the heterodyne oscillator itself, without change of coupling L_1L_4. The strength of each of these E.M.F.'s is measured by the corresponding current I_h in coil L_4, and the frequency by the capacity K of the oscillatory circuit of the heterodyne.†

Operation (*b*).—Tune heterodyne exactly to C_1L_1,‡ reducing its current to I_b so as to maintain M.V. reading at the former value E.

Operation (*c*).—Increase the heterodyne current from I_b to I_a, retuning the heterodyne (if necessary) exactly to C_1L_1, the capacity being then (say) K_0. The reading of M.V. is now somewhat greater than E, and is of no significance for the decrement determination.

* Such a value is convenient for reading on M.V., and vastly exceeds the signal E.M.F. applied to the grid of 4, while giving a response in T varying sensitively with the signal E.M.F., so enabling C_1L_1 to be tuned precisely by ear. With the low dampings employed, exact tuning of C_1L_1 is of course vital to the success of the measurements.

† The oscillatory circuit of the heterodyne oscillator was provided with condensers permitting accurate measurement of minute changes of capacity, and with vacuo-thermo-junction in series with L_4 for measuring I_h.

‡ It was distuned by (say) 500–1 000 periods per second in (*a*).

Operation (*d*).—Distune the heterodyne from capacity K_0 to K_d and K_d' (one above, the other below, K_0), causing the voltmeter reading to fall back in each case to E. Let k be the amount of distuning, where $k = \frac{1}{2}(K_d - K_d')$.

If C_1L_1 is the only oscillatory circuit in the receiver, it is easily seen * that its decrement [during operations (*a*), (*b*) and (*d*), but not (*c*)] is given by the formula

$$\delta = \frac{\pi k/K_0}{\sqrt{[(I_a/I_b)^2 - 1]}}$$

It has already been stated, however, that the impedance in the anode circuit of triode 3 was not in fact a pure resistance but was a rejector circuit like C_1L_1, although much more highly damped. This seriously complicates the analysis,† since the amplification in triode 3 is a step between circuit C_1L_1 and M.V., and also (which is more important) between C_1L_1 and the retroaction E.M.F. impressed therein from L_3. After operation (*a*) this impressed E.M.F. is a maximum and sensibly in phase with the oscillatory current in C_1L_1; and after the distuning it is necessarily to some extent reduced in magnitude and changed in phase. To establish the validity of the above formula for δ, it is therefore necessary to show that the magnitude of that component of the retroaction E.M.F. which is in phase with the current is altered to a negligible extent by the change of heterodyne frequency as between operation (*a*) and operations (*b*), (*c*) and (*d*). That such is the case in these experiments is shown in Appendix 2.

(3) Results Obtained.

Complete particulars of the dimensions of the circuits employed are given in Appendix 3. The resistances there shown are those of the oscillatory circuit measured at the relevant wave-length.

One typical series of observations—those on Marion—is given completely in Table 2; and the values of δ_1 and $n\delta_1$ for every observation made on all stations are collected in Table 3.

(4) Discussion of Results.

A very satisfactory feature of the results given in Table 3 is the close uniformity of the several observations on each station. It had been expected that far wider divergences would have been found, as the setting of the circuit [operation (*a*) in Section 2] was necessarily a matter of personal judgment. The precautions particularly desirable in such cases, to eliminate all influence on the observer of prejudice and expectation, were taken; not only were all adjustments upset between one observation and the next, but heterodyne currents of very unequal values were employed in the several observations on one station.

It could not be observed that the optimum damping was affected by the pitch of the heterodyne note,

* Appendix I.

† It was realized, after the observations had been made, that for the sake of simplicity of theoretical analysis it might have been wiser to put up with various experimental inconveniences involved in making this impedance substantially a pure resistance, or in retuning it between operations (*a*) and (*d*).

TABLE 2.

Typical Series of Observations.

Station, Marion. Wave-length 11 500 m.

Date	E	I_h	I_b	I_e	k	K_e	δ
	volts	mA	mA	mA	$\mu\mu$F	$\mu\mu$F	
3 Aug., 1923..	2·15	170	4·1	10·3	38	12 800	0·0041
4 Aug. ..	2·15	170	7·6	24·0	48	12 800	0·0039
6 Aug. ..	1·30	380	4·0	16·0	71	12 800	0·0045
7 Aug. ..	1·80	380	3·55	13·9	63	12 800	0·0040

TABLE 3.

Collected Observations (Jan. 1923–Aug. 1923).

Station	Type of oscillator	Wave-length	Date of observation	δ	$n\delta$
Ongar (Essex) ..	Triode	4 350 m	26 Jan.	0·00220	152
			28 Jan.	0·00184	127
			7 May	0·00188	128
			17 May	0·00237	163
			18 May	0·00210	145
			(Mean)	0·00207	142
Unknown	Probably triode ..	6 250 m	26 May	0·00314	145
			28 May	0·00315	145
			10 July	0·00318	147
			11 July	0·00292	135
			(Mean)	0·00310	143
Marion (U.S.A.) ..	Alexanderson alternator	11 500 m	3 Aug.	0·0041	107
			4 Aug.	0·0039	102
			6 Aug.	0·0045	117
			7 Aug.	0·0040	106
			(Mean)	0·0041	108
Carnarvon	Alexanderson alternator*	14 000 m	16 July	0·0045	100
			16 July	0·0058	124
			17 July	0·0056	120
			18 July	0·0051	108
			(Mean)	0·0052	113
Long Island (U.S.A.)	Alexanderson alternator	19 200 m	9 Aug.	0·0063	98
			10 Aug.	0·0065	101
			11 Aug.	0·0063	98
			(Mean)	0·0064	99
Bordeaux	Arc	23 450 m	13 Aug.	0·0084	108
			14 Aug.	0·0085	109
			15 Aug.	0·0084	108
			(Mean)	0·0084	108
				Total mean	= 119

* Information kindly supplied by Mr. R. N. Vyvyan, Engineer-in-Chief, Marconi's Wireless Telegraph Co.

provided that this was above about 500 periods per second.

Although the stations observed cover frequencies extending from 69×10^3 to 13×10^3 periods per second, the values of the product are seen to lie within the narrow range of 143 to 99. The view (referred to in Section 1) that it is the shape of the rising and falling portions of the amplitude time curves which determines the optimum decrement, is thus strongly supported. What, on this view, the critical "shaping" as demanded by the ear looks like to the eye is indicated in Fig. 2. Here the letter "C" as received is drawn for $n\delta = 100$, the curves of E.M.F. impressed from the transmitter being assumed sensibly square-topped in shape, and the speed of signalling being taken as 25 w.p.m.

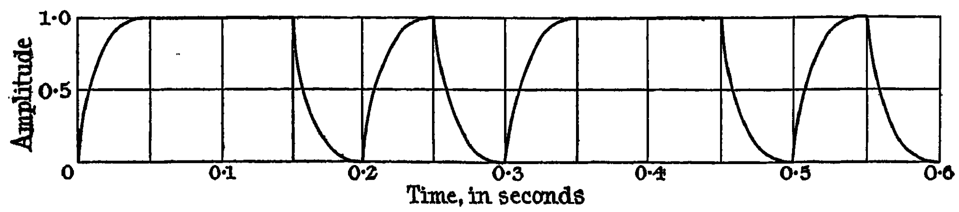

FIG. 2.—Letter "C" at 25 w.p.m. when $n\delta = 100$.

All the signals observed were of hand speed, and no attempts were made to measure any effect of changes of speed. The speeds did, of course, vary considerably from time to time; and no indication that the value of the optimum decrement depended on the speed was noticed. The authors' opinion is that, however much the speed of sending might be reduced, the optimum damping for auditive reception would not fall much below the values found in these experiments.

The optimum damping of the receiving circuit must, of course, depend on the sharpness of rise and fall at the sending antenna, the more the inertia there the less being the inertia tolerable in the receiver. It seems probable that the transmitter's share in the total inertia effects is small in comparison with that in a receiver in which $n\delta = 100$.* If it were not, the uniformity of the observations on stations covering so wide a range of wave-lengths, and including arc, alternator and triode generators, would be very surprising. It does not seem possible to infer from the observations any distinctions between the qualities of signalling, from the standpoint of the inertia effects we are studying, with these three different types of generator.

Summing up the positive results of the investigation, it may be concluded that the optimum damping for the auditive reception of signals from any modern continuous-wave station is such as to make the $n\delta$ of the receiving circuit of the order of 120, which corresponds to $\delta = 0\cdot0012$ at $\lambda = 3\,000$ m, and $\delta = 0\cdot008$ at $\lambda = 20\,000$ m; that such decrements are easily obtained by triode retroaction; and that with suitable care they may even be measured with considerable precision.

* The authors are not aware of any direct measurements of the rates of growth and decay of current in a sending aerial when the key is depressed and raised.

APPENDIX 1.

DERIVATION OF FORMULA FOR CALCULATING THE DECREMENT.

Let the circuit CLR in Fig. 3 represent the actual circuit $C_1R_1L_1$ with its triode retroaction and connections as in Fig. 1.* There is impressed in L from the heterodyne coil L_4 :—

In operation (b), an E.M.F. $\propto I_b$, of the resonance frequency $p/(2\pi)$, producing a current in CLR measured by the voltmeter reading E.

In operation (c), a larger E.M.F. $\propto I_c$, of slightly distuned frequency $q/(2\pi)$, producing sensibly the same current in CLR (since the reading E is unchanged, and the frequency is almost unchanged).

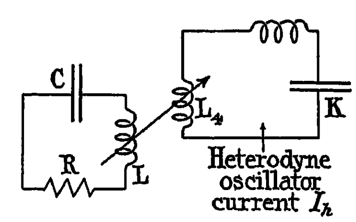

FIG. 3.

Now $q^2/p^2 = K_c/(K_c \pm k)$, and $p^2LC = 1$

$$\therefore \quad q^2LC = K_c/(K_c \pm k)$$
$$\doteqdot 1 \mp k/K_c$$

Hence
$$\frac{I_b^2}{R^2} = \frac{I_c^2}{R^2 + [qL - (1/qC)]^2}$$

i.e.
$$I_c^2R^2 = I_b^2\left[R^2 + \left(\frac{q^2LC - 1}{qC}\right)^2\right]$$
$$= I_b^2\left[R^2 + \frac{(k/K_c)^2}{q^2C^2}\right]$$

i.e.
$$\left(\frac{I_c^2}{I_b^2} - 1\right)R^2 = \left(\frac{k}{K_c}\right)^2 \frac{p^4L^2C^2}{q^2C^2}$$
$$\doteqdot \left(\frac{k}{K_c}\right)^2 p^2L^2$$

$$\therefore \quad \delta = \frac{\pi R}{pL} = \frac{\pi k/K_c}{\sqrt{[(I_c/I_b)^2 - 1]}}$$

* Taking a simple circuit with a constant resistance R to represent the actual retroactive arrangement may cause some apprehension; for the circuit is used with tuned and distuned impressed E.M.F.'s, and the "negative resistance" introduced by the retroaction depends to some extent upon the frequency. It can be shown, however, that in practical cases the effect of so small a distuning on the resistance of the equivalent simple circuit is quite negligible.

The utility of operation (*c*) lies in the fact that it gives the tuned value K_c of the heterodyne *after* the latter has been modified (by increase of filament current or otherwise) so as to increase its current from I_b to I_c. Such an alteration is apt to necessitate a small alteration of condenser value to hold the frequency constant, so that if the reading of K after operation (*b*) were taken in place of K_c it would be slightly inaccurate.

APPENDIX 2.

EFFECT OF ANODE CIRCUIT OF TRIODE 3 BEING AN OSCILLATORY CIRCUIT INSTEAD OF A PURE RESISTANCE.

The actual anode circuits of triodes 2 and 3, shown in skeleton in Fig. 1, were as shown in Fig. 4. We have to ascertain how the output anode voltage v_a of triode 3 is affected, with a given input grid voltage v_g, by distuning the v_g frequency from the resonance value $p/(2\pi) = 1/[2\pi\sqrt{(C_2L_2)}]$ to the slightly different value $q/(2\pi)$.

The impedance Z of the rejector circuit between anode and filament of triode 3 may be shown to be (dropping the suffixes 2)

$$Z = qL'\frac{\left[\frac{1}{qC} - qL''\left(1 - \frac{M^2}{L'L''}\right)\right] + jR}{R + j\left[qL - \frac{1}{qC}\right]}$$

where $j = \sqrt{-1}$.

At resonance the impedance is

$$Z_0 \doteqdot pL'\frac{\frac{1}{pC} - pL''\left(1 - \frac{M^2}{L'L''}\right)}{R}$$

Near resonance, when $q = p(1 + x)$, where $x << 1$,

$$Z_x \doteqdot Z_0 \frac{R}{R + j\left[qL - \frac{1}{qC}\right]}$$

$$= \frac{Z_0}{1 + j\frac{2\pi x}{d}} \qquad \text{where } d \equiv \frac{R}{2nL}$$

$$= Z_0\frac{1}{A}\underline{\left|\alpha\right.} \qquad \text{where } A \equiv \sqrt{[1 + (4\pi^2x^2/\delta^2)]}$$
$$\alpha \equiv \text{arc tan } 2\pi x/d$$

Calling ρ the anode-filament slope resistance of the triode (about 30 000 ohms) and ν the amplification factor, the performance of triode 3 is shown by the idealized circuit diagram and vector diagram of E.M.F.'s in Fig. 5. The output voltage v_a when tuned is OP, and when distuned is OQ. The distuning introduces negligible error in so far as OQ cos β (i.e. the resolved component of the retroaction E.M.F., distuned) is sensibly equal to OP (i.e. the retroaction E.M.F., tuned).

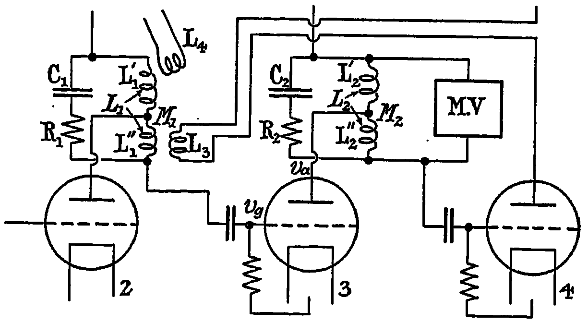

FIG. 4.—Anode circuits of triodes 2 and 3 in detail.

NOTE.—M_1, M_2 are the mutual inductances between the parts L_1', L_1'' and L_2', L_2'' of the coils whose whole inductances are L_1, L_2 respectively.

Now, since α and β are small angles,

$$\beta \doteqdot \alpha\frac{\rho}{Z_0 + \rho}$$

and

$$(\text{OQ cos } \beta)/\text{OP} \doteqdot \frac{(Z_0 + \rho)\frac{\alpha - \beta}{\alpha}\sqrt{(1 - \beta^2)}}{Z_0}$$

$$= \sqrt{(1 - \beta^2)}$$

$$\doteqdot 1 - \tfrac{1}{2}\beta^2$$

$$= 1 - \left(\frac{\rho}{Z_0 + \rho}\right)^2\frac{2\pi^2x^2}{d^2}$$

The circuit dimensions, tabulated in Appendix 3, enable us to evaluate this expression, bearing in mind that the distuning fraction x is half the ratio k/K_c of Section 2 and Table 2. The largest values of k/K_c, and the consequently worst values (i.e. departing most from unity) of (OQ cos β)/OP, in the observations on each of the several stations, are given in Table 4.

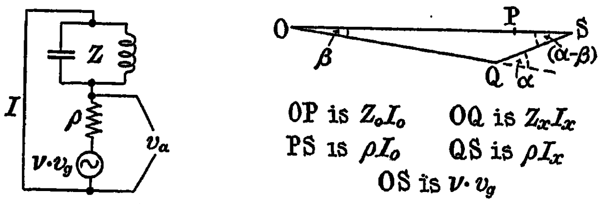

FIG. 5.—Action of amplifier 3.

In view of the closeness to unity of the last row of figures in Table 4, it is thought unnecessary to attempt to make allowance for the effect of distuning on the anode circuit of triode 3.

TABLE 4.

Station	Ongar	Unknown	Marion	Carnarvon	Long Island	Bordeaux
$(k/K_c) \times 10^{-3}$	1·97	4·9	5·5	7·3	7·8	7·1
(OQ cos β)/OP	0·995	0·978	0·999	0·998	0·996	0·983

APPENDIX 3.

Electrical Dimensions of Circuits (with Reference to Fig. 4).

Station	Wave-length	L_1'	L_1''	M_1	C_1	R_1	L_2'	L_2''	M_2	C_2	R_2
	metres	μH	μH	μH	μμF	ohms	μH	μH	μH	μμF	ohms
Ongar	4 350	790	2 040	310	1 550	23·5	740	1 880	320	1 630	23·0
Unknown ..	6 500	1 350	1 300	400	3 200	12·6	1 350	1 100	410	3 350	12·4
Marion	11 500	4 550	8 850	3 550	1 800	67·5	0	22 300	0	1 630	100
Carnarvon ..	14 000	4 550	8 850	3 550	2 850	51·0	0	22 300	0	2 600	69·0
Long Island ..	19 200	4 550	8 850	3 550	5 100	28·0	0	22 300	0	4 750	44·5
Bordeaux ..	23 450	4 550	8 850	3 550	7 650	24·5	0	22 300	0	6 950	37·5

Ongar and unknown station :—$L_1 = 3\,450$, $L_2 = 3\,260$, $L_3 = 260$, $L_4 = 150$ μH.
Other stations :—$L_1 = 20\,500$, $L_2 = 22\,300$, $L_3 = 3\,040$, $L_4 = 150$ μH.

The triodes were of the well-known "R" pattern. Common filament and anode batteries were used, the latter being of 120 volts.

Discussion before the Wireless Section, 4 February, 1925.

Prof. E. W. Marchant: As the authors point out, the determination of the most suitable wave-shape for a dot would appear to depend on psychological effects, and I should like to ask whether the observers who determined what they considered to be the best damping of the system (which, of course, determines the shape of the dot) were of approximately the same age; sharpness of hearing varies considerably as between old and young people, and there may also be differences due to the kind of telephone used. Why is it that a high anode potential is best in order to reduce the damping of the grid circuit? I take it that the real test for damping is low energy absorption. The slope of the characteristic curve is appreciably the same for most anode voltages and, therefore, one would not anticipate that there would be very much difference in the variation in grid current that would be taken by a valve with different anode potentials. The method of measuring the decrement by altering the tuning of the receiving circuit is, of course, the one that is usually adopted. The method described in the paper of altering the frequency of the current in the heterodyne circuit and adjusting the strength of the heterodyne current is one that should be particularly useful for measuring decrements in circuits, where it is desirable that no tuning adjustments should be made. The comparison between the results depends on the shape of the received signal current and that, as the authors point out, must depend on the shape of the dot emitted from the transmitting station. Other things being equal, a square wave at the transmitting end gives a closer approximation to a square wave in the receiving circuit. I do not think that the authors have obtained as much from their results as they might have done. For the three Alexanderson alternator stations the value of $n\delta$ works out at about 107. For the arc station, which has a very much longer wave-length, very nearly the same value of $n\delta$ is obtained. It would appear, therefore, that the squareness of the transmitting signal for these two types of station would be about the same. The two triode transmitting stations have a very much shorter wave-length, but very closely corresponding results (142 and 143) are obtained for $n\delta$, and it seems possible that the difference between the results for the alternator and arc stations and those for the triode stations may be due to differences in the squareness of the dot sent from the transmitting station.

Captain N. Lea: It would, I think, be of interest if the results set forth in the paper were translated into terms involving decrement at musical frequency. The tests were apparently carried out under conditions where static interference was practically negligible—that is to say, "readability" was a function of signal strength and "ringing" only, and not of "noise level"—and thus there should be no fallacy in applying the alternative interpretation of results. If, however, a musical decrement term is used instead of a radio-frequency decrement term, the former would almost certainly appear in the expression for "readability." I do not know whether the authors made any assumptions or any investigation in regard to the signal form of the transmitters which were observed. I believe that in several of the transmitters on which readings were taken an effort is made to increase the power of the dot, for instance, and in other ways to have some control over the rate of growth and decay of the current in the transmitting aerial. It occurs to me that this may have some effect on the results, though the uniformity obtained with the various stations suggests that there is, perhaps, not so much in this point.

Mr. R. V. Hansford: The paper is very useful in describing a method of measuring the decrement of a receiving circuit, and the splendid series of consistent results obtained is a great testimonial to its sensitivity and accuracy. One wonders, when one sees the extraordinary uniformity obtained for $n\delta$, whether the figure obtained is not in some manner a measure of the best adjustment of a particular type of receiver rather

than a general independent value of $n\delta$, and it would be interesting to know if measurements have been made on more than one type of receiver. The authors comment on the fact that the shape of the curve depends on the decrement of the circuit, and that the psychology of the individual is such that it is necessary to have a distinct break between the dash and the dot, but it seems questionable whether in a complex receiver the rise and fall of the signal current follow the simple law corresponding to the shape of signal given in Fig. 2. It seems possible that the " ringing," which the authors suggest is the limiting condition, is a function of the *shape* of the received signal and could be improved by deliberately modifying the shape, e.g. cutting off the bottom tails. In practice, the operator actually adjusts the decrement of his receiver within wide limits by varying the retroaction until he obtains the best conditions, and I should be glad to hear if, independently of the great scientific interest, the authors are able to draw any conclusion from their results in regard to practical receiver design.

Mr. R. E. H. Carpenter: Have the authors made any observations on stations which emit a spacing wave, particularly those which emit during the spacing period a feeble wave of the same frequency as that used for marking? It would seem that such observations might alter a little the conclusions to which the authors have come.

Major A. G. Lee: The measurement of the decrement of a circuit which is not retroacted is a comparatively easy matter, but when retroaction is present a number of difficulties present themselves. Some of these difficulties have not been discussed in the paper, and, while they may not relatively be of great importance, I propose to outline them for the sake of completeness. With reference to Appendix 1, which gives the derivation of the formula for calculating the decrement, the method adopted is one in which a mistuned oscillator is adjusted to give an output equal to that given by a weaker oscillator when the latter is adjusted to resonance. Now in the mistuned case the current in the circuit will be dependent upon the value of the impedance, viz. $\sqrt{[R^2 + \{qL - (1/qC)\}^2]}$. The variation of R with mistuning is dealt with by the authors in a footnote on page 497, which states that the effect is negligible. The reactance will, however, also be affected by the retroaction, and for mistuning which is not too wide the reactance varies much more rapidly with frequency than the same function does in a circuit without retroaction. The expression $\{qL - (1/qC)\}^2$ should therefore be replaced by one which takes into account the effect of the retroaction on the reactance. This effect has been worked out by Bennett and Peters.* A further point is whether the frequency of the heterodyne oscillator q is accurately given by the expression on page 497, viz. $q^2/p^2 = K_o/(K_o \pm k)$. If a valve oscillator is brought near a tuned circuit the frequency generated will be affected by the presence of that circuit, the effect differing according to whether the tune of the circuit is above or below the heterodyne oscillator frequency, so that k is not necessarily a measure of the change of frequency. Very loose coupling, which was adopted by the authors, is one of the means of reducing the discrepancy, and another more certain method is to use a screened heterodyne and to pass the output of the heterodyne oscillator through a unidirectional coupling such as a triode. The method adopted in which the combined signal and heterodyne currents are passed through a rectifying valve and the circuit of retroaction L_3, leads to the difficulty that it is not clear whether the retroaction is the same as it would have been if the signal only had been subject to retroaction. When the measurement is made the heterodyne oscillator alone passes through the retroaction circuits. It is not clear, for example, that the proportions of signal and heterodyne are the same after the process of grid rectification in triode 4 as they are before they reach that grid, or that the retroaction on the weak signal is the same as that measured by the aid of the powerful oscillator, owing to the action of the rectifier 4 through which the retroaction has to pass. During the positive peaks of the heterodyne the signal will be damped by grid current and the retroaction reduced. The phenomenon of " ringing " described by the authors is present on most wireless receivers when there is a very narrow band obtained by fine tuning. This ringing trouble appears to be due to the fact that the ear is not very sensitive to changes of amplitude of sound and does not appear to be able to distinguish in correct proportion the peaks and hollows of a signal which does not die away completely during the spacing intervals. The method adopted in commercial wireless receivers to overcome this defect is to use negative grid bias on some of the later stages of the receiver, such as the low-frequency portion. This process cuts off the hollows, and the ear now has definite periods of sound followed by equally definite periods of silence. The limit to this proceeding is, of course, that eventually the dots would disappear in the negative grid bias.

Messrs. L. B. Turner and **F. P. Best** (*in reply*): In reply to Prof. Marchant, no investigation was made as to the possible influence of age of observer, or pattern of telephone receiver used. No doubt there is a conceivable connection between youthfulness and sharpness of rise and fall, in acoustics as in other affairs; but we do not think that the kind of telephone could be of appreciable significance unless it possessed quite unusually low damping. The virtue of adequately high anode potential in avoiding grid damping is that it permits the use of sufficient negative grid bias to keep grid currents out of the question. With reference to the suggested distinction between the optimum values of $n\delta$ with triode transmitters on the one hand, and with arc and alternator transmitters on the other, the results, as far as they go, certainly point in the direction Prof. Marchant indicates. The distinction is the more remarkable in that the presumably greater steadiness or " purity " of the triode oscillation would tend towards lower decrements with the triode. The fact that the values of $n\delta$ appear to be distinctly higher with triodes than with arc or alternator, points towards greater keying inertia effects with the former than with the latter. We think, however, that the stations observed were too few to justify any but the most

* BENNETT and PETERS: "Resistance Neutralization," *Journal of the American Institute of Electrical Engineers*, 1922, vol. 41, p. 234.

tentative conclusion as to the relative qualities of the several types of transmitter.

Captain Lea's remarks imply, very truly, that in consideration of the effect on the ear the acoustic amplitude-time curves are of more direct interest than those for the high-frequency currents. But with the superposed heterodyne oscillation, the rectified current is proportional to the high-frequency amplitude; so that curves such as Fig. 2 may be supposed to portray approximately acoustic amplitude also. With the high damping of the acoustic system, and upwards of 25 acoustic (heterodyne note) cycles per morse dot, it is likely that the high-frequency and the acoustic amplitudes rise and fall in close concordance. It is noted in the paper (bottom of page 495) that reduction of the note to some low pitch did appear to affect results, and high pitches were employed in consequence.

Mr. Hansford wonders whether the surprisingly consistent values of optimum $n\delta$ may not be a property of one particular type of receiver. But, apart from a long chain of tuned circuits, we do not see how one receiver can differ from another, in its response to signals to which it is tuned, in other respects than sensitivity (which is irrelevant) and decrement (which we had under complete control). The influence of the "shape" of the received E.M.F. has been referred to in the paper and by several speakers (see our reply to Prof. Marchant above). The suggested possible improvement by some form of curbing has been referred to in the paper already published in the *Journal* (loc. cit., page 493). With regard to Mr. Hansford's concluding remarks, we do not wish to suggest that the information as to working decrements here afforded will be of any help to an operator in setting his instruments, but we do hope that it will be of use to the calculator who provides him with better instruments. In inquiries as to the effect of atmospherics in receiving circuits, for example, the lack of this knowledge has been acutely felt.

Two of the stations whose signals were observed were of the kind mentioned by Mr. Carpenter. Bordeaux used the distuned spacing wave, and Ongar the feeble continued emission between the marks.

Major Lee casts some doubt on the validity of the formulæ of Appendix 1, on three counts. First, he fears the distuning effect of the retroaction employed to reduce resistance. But this, we think, is a second-order effect which vanishes when the retroaction just reduces the decrement to zero; and in any case, whether great or small, it is no more than an experimental inconvenience, since the reactance of the circuit was maintained at zero by retuning during the retroaction adjustments [see under "Operation (*a*)," page 495]. Secondly, he fears that the coupling between L_4 and L_1 (Fig. 1) might make the frequency of the heterodyne depart appreciably from proportionality to the square root of its capacity K. We point in reply to the extreme looseness of the coupling between the heterodyne L_4 and the test circuit L_1C_1. Thus the heterodyne generated E.M.F.'s in its oscillatory circuit of the order of 100 volts. From this a minute E.M.F. is impressed on L_1 from L_4, so small that on multiplication by π/δ (say 500 times) in the circuit L_1C_1, and again between grid and anode in triode 3 (say a further 4 times, or 2 000 times in all), it produces only 1 volt or so on the measuring instrument M.V.; that is to say, the anode fluctuation of the heterodyne oscillator was some 200 000 times the E.M.F. it impressed on L_1C_1. Thirdly, he suggests that the decrement as measured, when only the heterodyne oscillation was present in the circuits, may have been appreciably different from its value in the system as adjusted for optimum reception in the telephone, when signal and heterodyne were present together. To this we can only reply that the amplitude of the signal was so small in comparison with the heterodyne as to produce no observable effect on the deflection of M.V., and point to the precaution taken with the triodes to reduce to a minimum "alterations of triode parameters consequent on minute unavoidable changes of amplitude while setting the receiver and measuring the decrement" (see top of page 495).

SOME ACOUSTIC EXPERIMENTS WITH TELEPHONE RECEIVERS.*

By Professor E. MALLETT, M.Sc., Member, and G. F. DUTTON, Ph.D., Student.

(*Paper first received 17th September, 1924, and in final form 13th January, 1925.*)

SUMMARY.

A Rayleigh disc is used to find the resonant frequency and decay factor of a telephone receiver under different circumstances as regards diaphragm clamping and air cavity behind the diaphragm. The field of sound in front of a resonator tube and a telephone receiver is investigated by the Rayleigh disc and by a device for measuring sound pressures, and direct measurements are made of the overall acoustical-electrical efficiency of a telephone receiver.

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INTRODUCTION.

Investigations of the properties of telephone receivers have received much attention in recent years and our knowledge of these instruments has been very largely increased, especially by the work of Prof. A. E. Kennelly and his various collaborators, now collected and published in book form.† In all of these investigations the method of attack has been by electrical measurements of the supply to the receiver, and by measurements of the actual movement of the telephone diaphragm. In the experiments described in the first part of the present paper an alternative method of attack is developed which depends upon measurements made on the sound wave produced by the receiver.

The particle velocity of the sound wave is measured by the well-known Rayleigh disc. The construction of a suitable form of disc, and its calibration, are described in Section (1). Measurement of the particle velocity in front of the telephone receiver, while constant current of variable frequency is passed through it, gives the resonance curve of the receiver, and from the resonance curve the resonance frequency and the decay factor can be obtained. That the values obtained in this way by measurements with the Rayleigh disc are the same as those obtained from electrical impedance measurements is shown by the experiments described in Section (2). With this established, the Rayleigh disc method, on account of its greater simplicity, is applied to investigate some of the outstanding problems of the telephone receiver. In Section (3) the unsymmetrical resonance curves very often obtained are shown to be due to imperfection of clamping of the receiver diaphragm, and a design of rigid clamping which gives symmetrical curves is described. Using this rigid clamping, the influence of the size of the air cavity behind the diaphragm on the resonant frequency and on the decay factor is examined in Section (4). It is found that as the cavity volume is decreased the resonant frequency is increased owing to the additional stiffness given to the diaphragm by the increasingly stiff air cushion. At the same time, the decay factor is increased, and the increase is measured with substances of different sound-absorbing properties forming part of the cavity walls. The results given in this section provide a ready means of tuning a diaphragm to a desired frequency, and indicate the importance of making all surfaces in the cavity smooth and rigid in order to avoid losses. In marked contrast with the fundamental, the influence of the air cavity on the overtone frequencies is shown to be negligible. Some interesting double-resonance effects are obtained in Section (5) by extending the cavity by means of a tube of variable length.

In the second part of the paper a direct measurement of the efficiency of a telephone receiver is made by measuring the electrical input power and the acoustical output power. The electrical input measurement is made by the use of a valve voltmeter in the well-known three-voltmeter method of power measurement. The measurement of the acoustical power output presents greater difficulties. The power from any acoustical source is the surface integration of the product of the particle velocity, the pressure, and the cosine of the phase angle between the two, carried out over any complete surface containing the source. But if the surface is a sphere with the source at the centre, and the radius of the sphere is sufficiently great, the sound wave has become at this surface a spherical wave with an equivalent point source at the centre of the sphere, and a single measurement of the particle velocity or the alternating

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† A. E. KENNELLY: "Electrical Vibration Instruments" [MacMillan].

air pressure is sufficient to determine the power output of the source.

This approximation to a spherical wave is shown to be true [see Section (6)] in the case of a source of sound consisting of a resonator tube excited by a telephone receiver, by the agreement with theory of the particle velocities measured at various distances along the axis of the tube. Except at frequencies close to resonance, however, the output of a receiver alone is insufficient to make this method applicable. So a more sensitive sound-measuring device is constructed [see Section (7)] consisting of a long thin tube opening out on to the diaphragm of a telephone receiver, the coils of which are connected through a three-stage amplifier to a valve voltmeter. This device is calibrated against the Rayleigh disc in the spherical field of sound produced by the resonator tube, and its indications are found to depend upon the pressure at its mouth. Finally [Section (8)] this device is used to explore the field of sound around a telephone receiver fitted with a large flange, to find the least radius at which the wave may be considered to be hemispherical, and so to make measurements of the acoustical output. Close to resonance of the receiver, where the pressure explorer fails owing to its own resonance nearly coinciding, the Rayleigh disc is used for the measurement. The overall efficiency of the receiver measured is found to be about 1 per cent at resonance, falling to 0·1 per cent at a frequency removed from resonance by about 200 cycles.

Part I. Use of Rayleigh Disc in Telephone Receiver Experiments.

(1) The Construction and Calibration of a Rayleigh Disc.

Experiments such as the determination of the efficiency of telephones and microphones, the resonant frequencies and damping of telephone discs and loud-speaker horns, require sound-measuring devices which have no reaction upon the source and which can be accurately calibrated. The Rayleigh disc, used without any resonator, suggests itself for the measurement of the vibrating air velocity. Its calibration may be performed accurately with unidirectional air flow.

König * has from theoretical considerations determined the following relation connecting the torque upon a thin circular disc and the gas velocity:—

$$\text{Torque} = \tfrac{4}{3}\rho r^3 v^2 \sin 2\theta$$

where ρ = density of the gas,
v = velocity of the gas,
r = radius of the disc,
θ = angle which the normal to the disc makes with the direction of gas flow.

If the stream of gas is alternating in direction, such as in a sound wave, the velocity v will be the R.M.S. velocity of the gas.

The torque produced on a disc is very small for low gas velocities; with a disc 0·5 cm diameter and velocity of air 0·5 cm/sec. (R.M.S.) the torque developed is 0·0438 dyne-cm when $\theta = 45°$; at a frequency of about 500 cycles per sec. this velocity represents a loud sound.

* *Annalen der Physik und Chemie*, 1891 vol. 43, p. 43.

A thin mirror 0·5 cm in diameter suspended by unspun silk was at first employed. It was sensitive but its zero was not sufficiently stable. Very thin phosphor-bronze strip (1 mil wire, rolled) was tried but found to be too stiff, but exceedingly thin glass fibre was found to be perfectly stable and sensitive. The fibre was made by C. V. Boys's method of making quartz fibres. It was found that unless the mirror was very thin and light, considerable difficulty was encountered due to lack of sufficient damping. Silvered microscope cover-slips answer admirably. Such a disc 5 mm in diameter

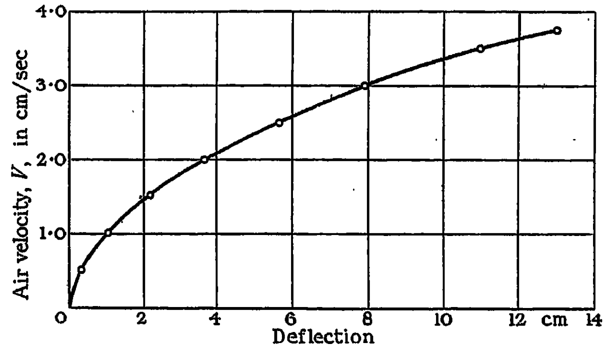

Fig. 1.—Rayleigh disc calibration.

with a glass-fibre suspension will come to rest, after being violently disturbed, in 2 or 3 seconds.

Since the elastic constants of the suspension fibre were not known, it was decided to calibrate the disc in a direct current of air. The disc was suspended in the centre of a tube 5 cm diameter, in a current of air caused by the displacement of water in a tank. The rate of flow of the water in the tank was observed, and from the knowledge of the respective areas of the tank and tube the air velocity was deduced. With air velocities above 2 cm per sec., however, the air flow was very erratic, due to the formation of eddies in the water

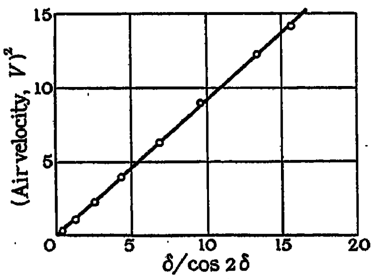

Fig. 1 (*a*).

pipes and valve. To surmount this difficulty a sensitive inclined Venturi meter was constructed and calibrated. Velocities above 2 cm/per sec. were then obtained with the use of this meter and a rotary air pump. A large air reservoir was placed in series with the air supply from the pump to eliminate slight pulsations.

The deflection of the disc mirror was observed by means of a lamp and scale. The initial position of the plane of the mirror was 45° to the direction of air flow, the length of the suspension fibre was 39 cm, and the distance of the disc to the scale 48 cm.

Fig. 1 shows the calibration curve obtained for this

disc, where the air velocity in cm per sec. is plotted against the deflection a. Fig. 1 (a) gives a verification of the formula Torque $= KV^2 \sin 2\theta$. For equilibrium the torque $= A\delta$, where δ is the angle of deflection of the disc, and is given by $\tan 2\delta = a/d$, where d = distance from scale to disc = 48 cm. When the disc is deflected by an angle δ, the angle θ of the formula becomes $(45 - \delta)$, and $\sin 2\theta = \sin (90 - 2\delta) = \cos 2\delta$.

Hence $A\delta = KV^2 \cos 2\delta$, or $V^2 = \text{const.} \times \delta/\cos 2\delta$. The relation between V^2 and $\delta/\cos 2\delta$ should be a straight line, and that this is very nearly true for the curve of Fig. 1 is shown in Fig. 1 (a).

The calibration of the disc carried out in a steady air current by theory holds for an alternating air current of any telephone frequency. This is confirmed by later experiments, which indicate that the disc calibration is independent of frequency.

(2) Receiver Resonance Curves.

A Rayleigh disc calibrated in this way was used to find the resonance curve of a receiver diaphragm, and hence its decay factor and resonant frequency, and

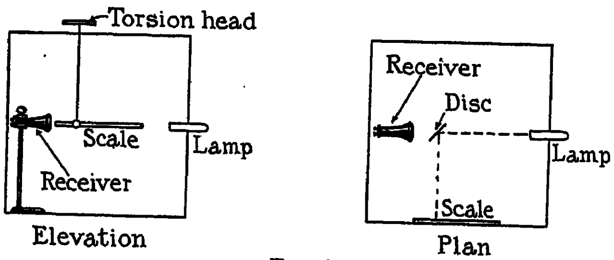

Fig. 2.

at the same time impedance measurements were made so that the values obtained could be compared with those obtained by the method described previously.* Power of known frequency was obtained by actuating a triode amplifier with a valve oscillator, care being taken that the anode voltage and grid voltage of the amplifier were so arranged that no load was placed on the oscillator. In this way the frequency calibration of the oscillator is not interfered with by current changes in the telephone. The oscillator was calibrated against the fundamental and harmonics of a valve-maintained tuning-fork by adjusting the capacity of the oscillator until beats from telephones in the anode circuits of the maintained fork and the amplifier disappeared. The value of K in the relation

$$\text{Frequency} = \frac{K}{\sqrt{\text{(capacity)}}}$$

decreased slightly with rise of frequency. A curve connecting K and the capacity was drawn so that the frequency could be determined on a slide-rule from the value of the capacity.

A sound chamber was made of a wooden box 1 metre cube, the inside walls of which were coated with a 4-in. layer of loose cotton waste. Such walls, as will be seen in later experiments, are sufficiently sound-absorbent to prevent any trouble from reflected waves.

* E. Mallett: *Journal I.E.E.*, 1924, vol. 62, p. 517.

The receiver under investigation was supported by a retort stand in this chamber. A torsion head on the top of the box carried the Rayleigh disc, which was illuminated by a lamp in the side of the box opposite the receiver, and the deflections of the disc were read on a translucent scale let into the side of the box next to the lamp (see Fig. 2). The zero position of the disc was adjusted by means of the torsion head so that its normal made an angle of 45° with the axis of the telephone and hence with the sound wave from the telephone.

The current to the receiver was supplied from a step-down transformer in the anode circuit of the amplifier valve, and included in the receiver circuit was a Duddell thermal milliammeter and a variable resistance. A valve voltmeter was connected across the receiver terminals, and the resistance always adjusted so that the voltage was the same, viz., 2·2 volts. The impedance at any frequency was therefore $2 \cdot 2/i$, where i is the current reading on the milliammeter.

Table 1.

Comparison of Damping and Resonant Frequency by Impedance Measurement and by Rayleigh Disc. Potential Difference across Receiver = 2·2 volts.

Frequency	Current	Air velocity V	Z	V/i
~/sec.	mA	cm/sec.	ohms	cm/sec./amp.
613	8·6	0·35	256	40·6
637	8·35	0·45	264	54·0
651	8·1	0·55	272	68·0
704	7·3	1·35	301	185
711	7·58	1·85	290	244
716	8·2	2·25	268	275
723	9·0	2·55	244	284
739	10·33	2·55	212	247
753	10·25	1·85	214	180
775	9·5	1·25	232	132
797	8·95	0·85	246	95
850	8·13	0·45	270	55

The force actuating the diaphragm is proportional to the current, and the diaphragm velocity at any frequency is given by

$$\dot{x} = \frac{F}{z} = \frac{Ai}{z}*$$

where F is the alternating force, A the force factor and z the mechanical impedance of the diaphragm. The air velocities V in front of the receiver will presumably be proportional to the diaphragm velocities, so that

$$V \propto \dot{x} \propto \frac{Ai}{z}$$

or $\frac{V}{i} = \frac{B}{z}$, where B is a constant.

To obtain a resonance curve $(1/z)$ of the diaphragm, V/i must therefore be plotted against the frequency.

The figures obtained in this experiment are given in Table 1. In the first column is the frequency, in the

* Kennelly, *loc. cit.*, p. 93.

second the current through the receiver, and in the third the R.M.S. air velocity as measured by the Rayleigh disc. The calculated value of the receiver impedance ($Z=2\cdot2/i$) is entered in the fourth column, and the air velocity per ampere (V/i) in the fifth. Z is plotted against the frequency at the top of Fig. 3, and V/i below. The circle construction previously described* is carried out on each curve to obtain the tan α/frequency lines at the bottom of the diagram. It is seen that these lines very nearly coincide. The decay factor Δ from each is 146, while the resonant frequencies are 721 from the impedance measurements and 724 from the Rayleigh disc measurements.

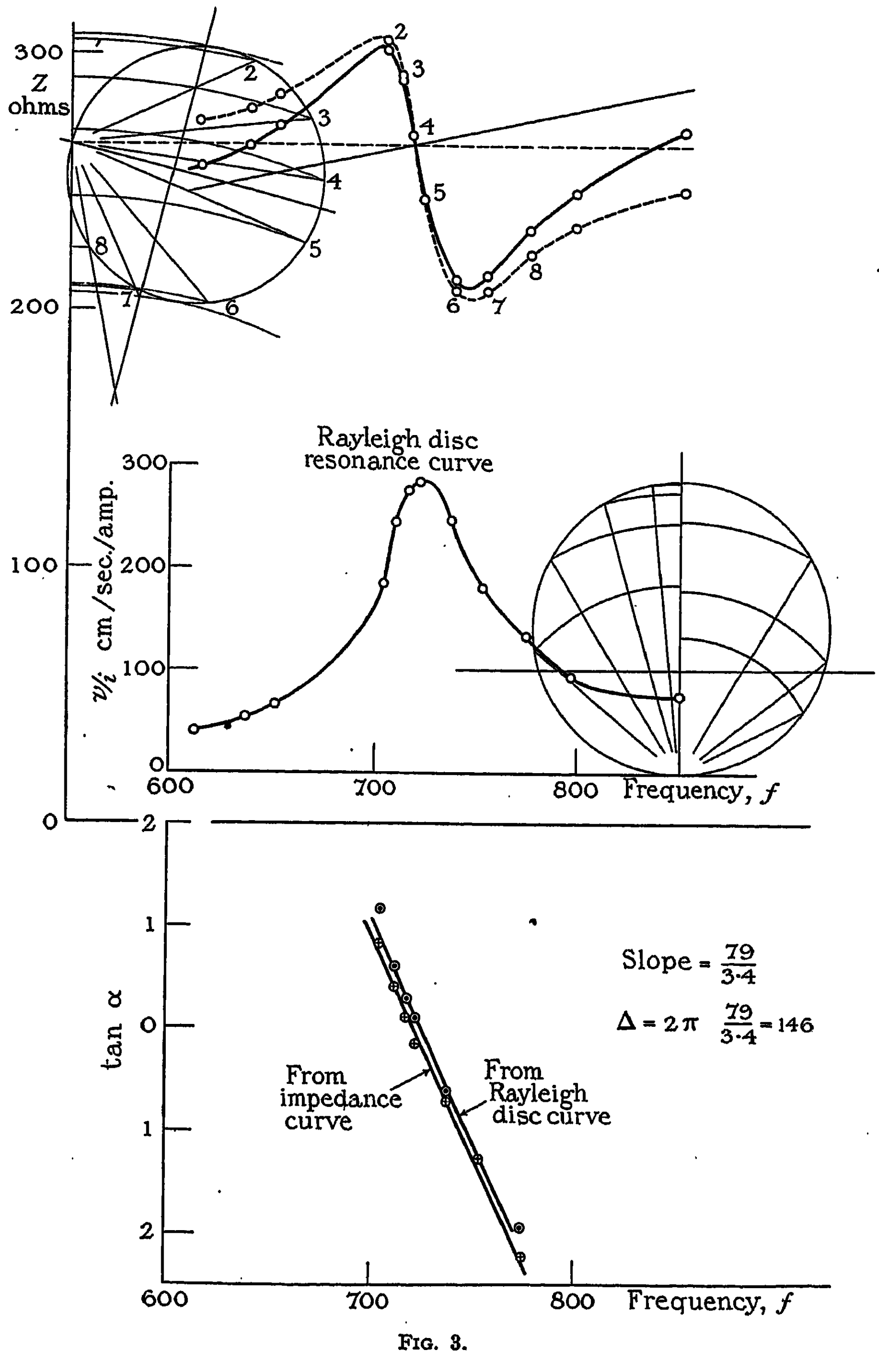

FIG. 3.

It is evident, therefore, that the Rayleigh disc method gives essentially the same values as the impedance method for the resonant frequency and decay factor of the diaphragm, and it was used as a general method in further investigations in preference to the impedance method, on account of its greater simplicity.

* E. MALLETT, *loc. cit.*

In order to reduce the time taken for the disc to come to rest after any adjustments of current or frequency, a key was included in the receiver circuit so that the current supply could be stopped or reduced so as to give, by reason of the altered sound-wave intensity, a judicious impulse to the disc.

(3) Lack of Symmetry in Resonance Curves.

A lack of symmetry was very often observed in the resonance curves obtained from receivers with the diaphragm clamped in the usual way with a screw cap of ebonite, for example in the curve of Fig. 4 for an

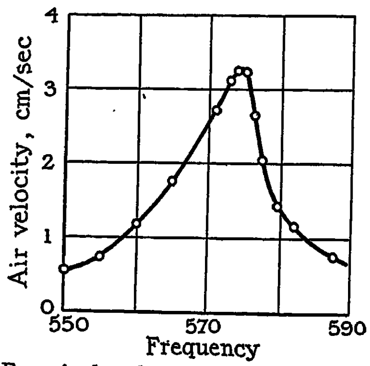

Fig. 4.—For single-pole receiver; diaphragm clamped with ebonite screw-cap.

old single-pole receiver. Here the rise of amplitude while approaching the maximum from low frequencies is much slower than the fall of amplitude after the maximum has been passed. In other cases the reverse has been found. Kennelly * has noticed a similar departure from the theoretical resonance of a single system, and suggests in the discussion on a paper by Prof. R. L. Jones on "Vibration Galvanometers with Asymmetric Moving Systems" (*Proceedings of the Physical Society*, 1923, vol. 35, p. 67) that it may be caused by asymmetry introduced by uneven clamping

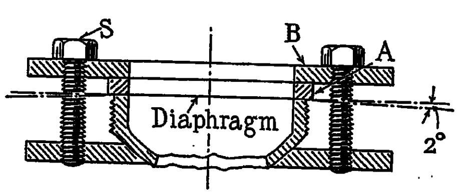

Fig. 5.

of the diaphragms round the edge. That asymmetry exists generally is also noted in a paper † in which the nodal lines of various overtones of a receiver diaphragm were mapped out by sand figures, and was indicated by the appearance of nodal diameters at two different frequencies. The asymmetry was also indicated by the departure of the nodal circle from a true circle into ellipses or pear-shaped figures. In fact the clamping of the diaphragm in those experiments was adjusted until the figure was most nearly a circle.

The receiver from which Fig. 4 was taken was accordingly modified as indicated in Fig. 5 by replacing the ebonite screw-cap by a brass ring A, both the ring and the receiver case being ground slightly conical so that, when the heavy clamping ring B was screwed up tight by the set-screws S, the diaphragm was slightly stretched. The resonance curve now obtained is given in Fig. 6. The asymmetry has disappeared, while the resonant frequency has been raised from 575 to 718 cycles per second, partly owing to the stretch given to the diaphragm but, probably, also owing to the more rigid clamping obtained. It was found, moreover, that only one resonance was obtained for the nodal diameters, and that the nodal circle was apparently a true circle.

It appears therefore that, for experiments on tele-

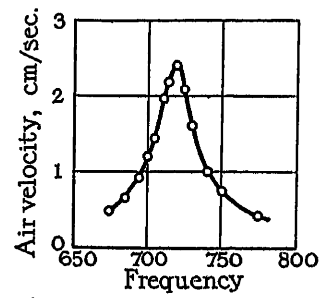

Fig. 6.—For single-pole receiver; diaphragm clamped with heavy brass ring.

phone receivers, clamping in the ordinary way with a screw cap is not satisfactory, but that an arrangement such as the one indicated in Fig. 5 gives perfectly satisfactory results.

(4) The Influence of the Air Chamber on the Resonant Frequencies and Damping of a Telephone Diaphragm.

It has been noticed * that the ratios of the overtones of a telephone diaphragm to the fundamental do not

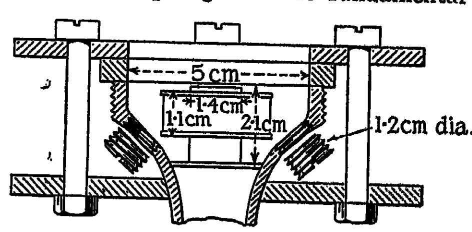

Fig. 7.

conform with either the membrane or the plate theory, but that the ratios of the overtones to the nodal circle agree quite well with the plate theory. Investigations were carried out to ascertain the effect of the air cavity behind the telephone diaphragm upon the resonant frequencies of the fundamental and overtones, with the hope of explaining the apparent departure of the fundamental from the plate theory.

A telephone of the dimensions shown in Fig. 7 was used. The diaphragm was of stalloy 5 mils thick with the enamel removed. It was clamped by a heavy brass ring and four set-screws, with the clamping surfaces

* *Loc. cit.*, p. 128.

† J. T. MacGregor-Morris and E. Mallett: *Journal I.E.E.*, 1923, vol. 61, p. 1134.

* J. T. MacGregor-Morris and E. Mallett, *loc. cit.*

ground dead flat, so that the diaphragm was neither stretched nor buckled when clamped. Under these conditions a true smooth resonance curve was obtained for the fundamental and the first nodal circle. Four

TABLE 2.

Mode	Infinite cavity		Air cavity 24 cm^3		Plate theory $\frac{\text{Overtone}}{\text{Fundamental}}$
	Resonant frequency	$\frac{\text{Overtone}}{\text{Fundamental}}$	Resonant frequency	$\frac{\text{Overtone}}{\text{Fundamental}}$	
Funda-mental	512	1·00	620	1·00	1·00
	1 073	2·13	1 073	1·73	2·10
	1 724	3·37	1 724	2·78	3·40
	1 985	3·80	1 985	3·20	3·90
	2 582	5·02	2 582	4·17	5·00
	3 064	6·00	3 064	4·95	5·95
	3 275	6·40	3 275	5·29	—
	4 300	8·40	4 300	6·94	8·30
	4 460	8·91	4 460	7·20	8·70
	5 830	11·40	5 830	9·40	—

screw plugs 1·2 cm in diameter were tapped into the air cavity casing. With these plugs removed the cavity volume was considered to be infinite.

The resonant frequencies were obtained, for all modes by the ear and the nodal figures were shown by light dry sand.

Table 2 shows the ratios of the higher modes to the fundamental for an infinite cavity and for a cavity volume of 24 cm^3. When the cavity volume is infinite these ratios conform very accurately with those calculated from the theory of a circular plate rigidly clamped at its edge. With a cavity volume of 24 cm^3 all the ratios are too small. The fundamental of the diaphragm has been raised by the increase of stiffness given by the air cavity, while the frequencies of the overtones are not affected.

In order to obtain a relation between the resonant frequency and air cavity a standard telephone was used. The diaphragm was enamelled to an equal thickness on either side, the total thickness of enamel being 5 mils and of the metal 7 mils. The variation of the cavity volume was obtained by pouring in paraffin wax; a period of at least four hours was allowed for the wax to cool and harden before observations were made. The volumes were measured by pouring fine silver sand into the cavity up to the diaphragm level and then pouring the sand from the cavity into a calibrated tube. In taking the resonance curves the Rayleigh disc was suspended at a distance of 2 cm from the diaphragm, and the receiver was actuated by a constant current of 2 mA for the fundamental and 4 mA for the nodal circle.

The curves obtained for the fundamental are shown in Fig. 8, while Fig. 8 (*a*) gives the curve obtained with each cavity for the nodal circle. It is seen that while the reduction of cavity results in a successive increase of resonant frequency in the case of the fundamental, it has no influence on the nodal circle curve. The two curves with different dampings at a cavity volume of 13·6 cm^3 are dealt with later.

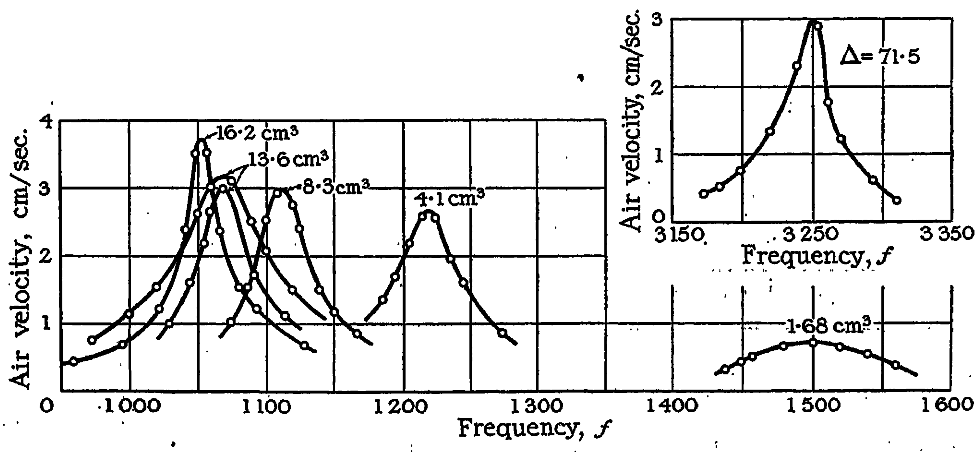

FIG. 8.—Resonance curves for fundamental with various cavity volumes.

FIG. 8 (*a*).—Resonance curve for nodal circle overtone.

up to and including the nodal circle, by means of the Rayleigh disc suspended at a distance of 2 cm from the diaphragm. Plotting air velocity against frequency with constant exciting current, the maximum or peak velocity gave the resonant frequency direct. For higher modes than the circle the resonant point was detected

These results may be explained by the consideration that the pressure alterations of the air in the cavity give rise to an additional restoring force on the diaphragm, and this restoring force for a given diaphragm movement will be inversely proportional to the volume of the air cavity.

Under ordinary circumstances the resonant frequency of a diaphragm is given by

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{S}{m}}\ *$$

where S is the restoring force for unit deflection and m the equivalent mass. If to S we add a quantity $S' = A/v$, where v is the cavity volume, we obtain

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{(S + S')}{m}}$$

from which

$$f_0^2 = \frac{1}{4\pi^2}\left(\frac{S + S'}{m}\right) = \frac{1}{4\pi^2}\left\{\frac{S}{m} + \frac{A}{vm}\right\}$$

$$= B + \frac{C}{v}$$

where A, B and C are constants.

Thus f_0^2 plotted against $1/v$ should give a straight line.

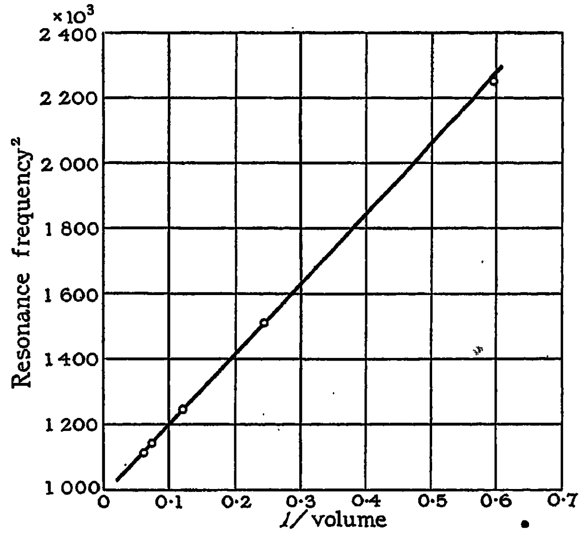

FIG. 9.

In Table 3 are entered the values of f_0 and v from Fig. 8, and the values of f_0^2 and $1/v$ are plotted in Fig. 9.

TABLE 3.

v	f_0	$1/v$	$f_0^2 \times 10^{-3}$	Δ
cm³				
16·2	1 055	0·0617	1 112	84·9
13·6	1 068	0·0736	1 140	167 and 105
8·34	1 115	0·120	1 244	99·3
4·10	1 230	0·244	1 511	124
1·68	1 500	0·595	2 251	314

The points obtained lie on a straight line, thus confirming the explanation given above of the influence of the air cavity.

Fig. 8 (a) shows the resonance curve for the nodal circle overtone. The resonant frequency and damping of this overtone were found to be independent of the air cavity volume down to 1·68 cm³. In the case of the overtones, therefore, there is no communication of alternating air pressure to the cavity as a whole; the outward displacements of parts of the diaphragm are at any instant equal to the inward displacements of the other parts. A reciprocating air flow must take place between the parts of the diaphragm of opposite phase, and not until the cavity is so small as to impede this flow will an alteration of reasonant frequency and damping be expected.

It is thought that these results may explain to some extent the lack of success of the static method of finding the stiffness coefficient of a telephone diaphragm.* The increase of deflection with time of application of load described by Kennelly may be due to the gradual leaking away of air from the cavity, while if the cavity is open to the air through the holes through which the leads are brought, the static determination of the coefficient will not include the stiffness due to the air cushion.

The values of the decay factor $r/(2m)$ derived from the curves of Fig. 8 are entered in the last column of Table 3, and it is at once evident that the volume of the cavity has a large effect upon the damping. The increase of damping with reduction of volume was, however, somewhat irregular in the first readings taken, and it was thought that this might possibly be explained by the surrounding of the coils of the receiver by wax. This supposition was to some extent confirmed by the second figure at $v = 13·6$, which was obtained by boring out some of the wax after it had been nearly full so that now when the receiver coils were nearly completely covered with wax the decay factor was 105, whereas previously when the coils were almost completely exposed, but the cavity volume was the same, the value was 167.

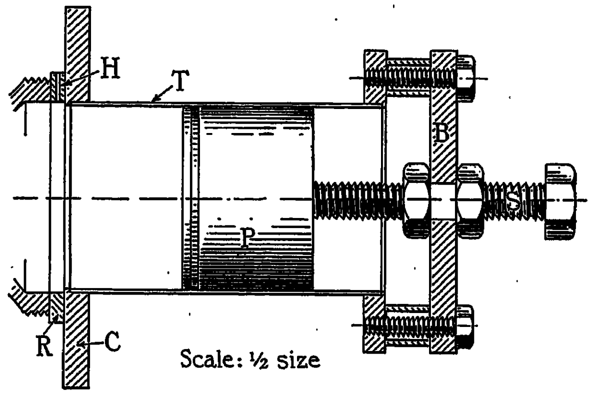

FIG. 10.—Variable air cavity.

Obviously, therefore, the method by adding wax is not a good way to investigate the influence of the air cavity on the damping, and a special device was constructed as shown in Fig. 10, in which an artificial adjustable cavity is fitted on to the front of the telephone, while the normal cavity behind the diaphragm was opened to the atmosphere by removing the plugs shown in Fig. 7. T is a brass tube, 4·9 cm long, sweated into

* KENNELLY, *loc. cit.*, p. 47.

* KENNELLY, *loc. cit.*, p. 41.

the telephone clamping ring C. Within the tube slides an airtight boxwood piston P. The space between the piston and the telephone diaphragm forms the air cavity, the volume of which may be adjusted to a nicety by the screw S and lock-nuts working between the bridge B. To relieve the pressure in the cavity after an adjustment of volume, a taper pin is withdrawn from the hole H in the clamping ring. A Rayleigh disc was suspended in front of one of the holes in the cavity casing, and the whole apparatus was placed in the sound chamber to screen the suspended disc from draughts.

The variation of damping factor with volume was determined with the piston face covered with :—

(i) Smooth brass 0·4 cm thick.
(ii) Hard felt 0·5 cm thick.
(iii) Vaseline 0·2 cm thick.

The results are given in Table 4 and the decay factor is shown plotted against 1/volume in Fig. 11. The

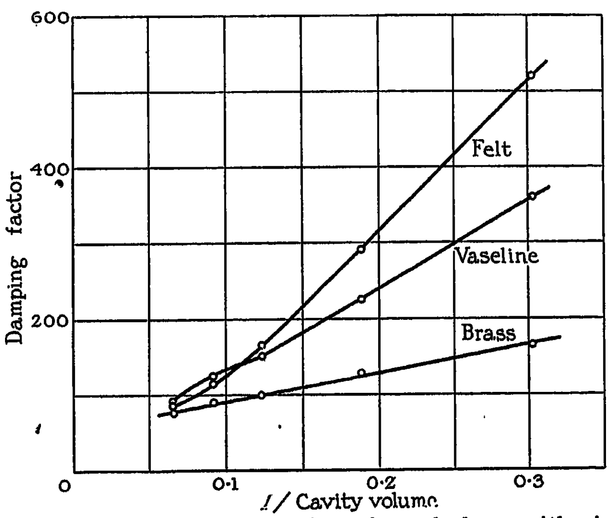

FIG. 11.—Variation of damping of a telephone with air cavity volume and material.

readings for brass give an approximately straight line. Probably the energy loss does not take place to much extent on the surface of the thick brass but is mainly due to air leakage.

TABLE 4.

Volume	1/volume	Damping factor		
		Brass	Felt	Vaseline
cm³				
15·0	0·0667	76·8	87	90
10·7	0·0935	89·0	115	112
8·1	0·1235	100·0	165	150
5·3	0·1890	128·0	290	224
3·3	0·3030	165·0	520	360

The damping factors for felt give a curve which has a tendency to become steeper as the air volume is reduced. The departure from the straight line may be due to the error in the measurement of the air volume, for the felt has a very rough surface. The damping factor for vaseline is at first greater than for felt, but the average slope of the curve is less, the result being that at 3·3 cm³ the damping is 360, while that for felt is 520. The values for vaseline give a very fair straight line. It should be mentioned that the vaseline contained numerous very small air bubbles, and it would therefore be imagined that losses took place owing to the viscosity of the air in these small bubbles and to that of the vaseline round about them.

These experiments show that the acoustical-electrical efficiency of a telephone will depend to some extent upon the air cavity volume and the material of its walls. For large cavities such as 15 to 20 cm³ and with the standard size of diaphragm the effect of different materials will be small, but if small cavity volumes are used the material of the cavity will be a matter of considerable importance. In such cases the insulating material of the windings should be consolidated with wax or, better still, the windings should be enamelled solid. Some commercial telephone receivers have this feature. The reminder of the cavity walls should be of smooth metal, free from air leakage to the external atmosphere or to the receiver handle.

(5) EXTENSION OF CAVITY.

An adjustable air column in the form of a long brass tube was coupled direct to the air cavity behind the telephone receiver by screwing the tube in the casing. The tube was 30 cm long by 1 cm bore, fitted with an airtight piston packed with greased leather. By adjusting this piston the length of the air column could be varied at will from 0 to 28 cm. It was found necessary to equalize the pressure on either side of the diaphragm between each variation of air-column length, by withdrawing a small plug (formed by a knitting-needle) from a hole in the cavity casing.

The telephone was placed in the padded sound chamber with the diaphragm 2·8 cm from the Rayleigh disc. Resonance curves for various lengths of air column were then taken with constant current over a frequency range of 200–3 000 cycles. There was a slight fall in the fundamental resonant frequency according to the theory of Section I (*d*), until the air column was about 10·5 cm long, but beyond this point a double-resonance effect appeared.

Resonant curves are shown in Fig. 12 for air-column lengths of 10·6, 11·6, 14·7 and 19·9 cm. Between tube lengths of 10 and 20 cm, since only two resonances could be detected, it may be concluded that the fundamentals of the diaphragm and of the tube only were acting as a coupled system. No double resonance could be obtained with the overtones of the diaphragm. This confirms the conclusion arrived at in Section 1 (*d*) that a diaphragm vibrating in an overtone produces no change of air pressure in the cavity.

The arrangement is analogous in many ways to the familiar coupled electrical circuits. In such a system, referring to Fig. 12, if OA = OB = natural wave-length of one circuit λ_1, OC = natural wave-length of the other circuit λ_2, and $\sin\theta = \sin \mathrm{COB} = \tau$, the coupling coefficient, then the two wave-lengths λ', λ''

at which resonance appears are given by $\frac{1}{2}$(AC + CB) and $\frac{1}{2}$(AC − CB).*

In Table 5 and Fig. 12 it is shown how far the mechanical coupled system in question agreed with the electrical laws.

When air columns greater than 23 cm were tried, double resonance again occurred, the column then vibrating on its third harmonic.

The application of this investigation is to the loud-speaker, where the horn with its various resonant frequencies must act in a similar manner to the tube in causing multiple resonance frequencies.

TABLE 5.

1 Tube length, l	2 Resonant frequencies		3 Resonant wave-length		4 $(\lambda' + \lambda'')$	5 $(\lambda' - \lambda'')$	6 Wave-length of tube, $4l$	7 Wave-length of tube, from construction
			λ'	λ''				
cm 0	715		47·0		—	—	—	—
10·6	670	910	50·0	36·8	86·8	13·2	42·4	41·0
11·6	650	855	51·5	39·2	90·7	12·3	46·4	45·0
14·7	590	770	56·8	43·5	100·3	13·3	58·8	54·2
19·7	476	735	70·4	45·6	116·0	24·8	79·6	69·5

In cols. 1 and 2 are collected the data of Fig. 12. In col. 3 are entered the resonant wave-lengths (λ' and λ'') calculated from col. 2 as 33 500/f.

In Fig. 13 we have

$$\lambda' = \tfrac{1}{2}(AC + CB)\,; \quad \lambda'' = \tfrac{1}{2}(AC - CB)$$
$$\therefore \lambda' + \lambda'' = AC \quad \text{and} \quad \lambda' - \lambda'' = CB$$

$\lambda' + \lambda''$ is entered in col. 4 and $\lambda' - \lambda''$ in col. 5, and these values are used to construct the wave-length triangles, taking AO = OB = 33 500/715 = 47·0, the natural wave-length of the diaphragm with air cavity.

In col. 6 is entered the wave-length of the tube (4 times its length) and in col. 7 the wave-length measured off as OC from the triangles. The agreement is not too good, and the analogy is probably not complete, but it is sufficiently good to show the points of similarity.

The "coupling coefficient" varies from sin 15·2° (= 0·28) in the case of the 10·6 cm tube, to sin 10·6° (= 0·18) in the case of the 19·7 cm tube.

* PIERCE: "Electric Oscillations and Electric Waves," p. 81.

Part II. ACOUSTICAL-ELECTRICAL EFFICIENCY OF TELEPHONE RECEIVER.

(6) A SOURCE OF SOUND OF PURE AND VARIABLE FREQUENCY.

The well-known equation for the actuating force on a telephone diaphragm is :—

$$\text{Force} = K\{B_0^2 - (B_0 + b \sin \omega t)^2\}$$
$$= -K\{2B_0 b \sin \omega t + \tfrac{1}{2}b^2 - \tfrac{1}{2}b^2 \cos 2\omega t\}$$

where B_0 is the permanent flux,
b is the R.M.S. alternating flux due to the current in the windings, and
ω is the angular velocity.

It will be seen that if the alternating flux b is so large that its square is comparable with $B_0 b$, then the second harmonic will be appreciable.

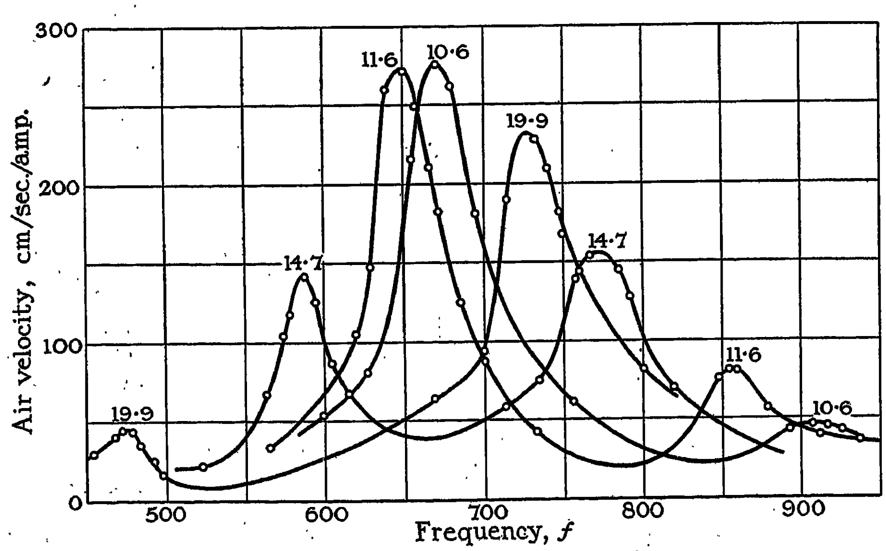

FIG. 12.—Resonance curves for telephone coupled with closed air column.

Again, the restoring force per unit displacement is not symmetrical about the zero, hence a full series of harmonics of rapidly decreasing amplitudes with increase

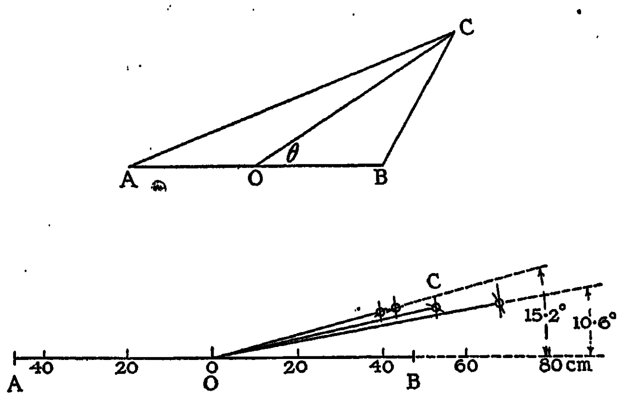

FIG. 13.

of frequency is likely to occur if the amplitude of vibration is large. The second, however, is the only harmonic that is likely to be appreciable.

Resonance curves were taken with a fixed frequency and current and variable tube length. Fig. 16 shows such a curve. It will be seen that the resonances are very sharp, hence if the tube is to give a steady sound output the frequency of the supply must be kept very constant. The distances apart of the peaks are half the wave-length, and the small decrease of amplitude with successive peaks shows how small is the damping introduced by the tube walls.

THE DISTRIBUTION OF SOUND INTENSITY ABOUT THE RESONATOR TUBE, AND THE CALIBRATION OF A TELEPHONE SOUND-PRESSURE EXPLORER.

The shape of a sound wave proceeding from an open tube changes rapidly from a more or less plane wave within the tube to a spherical one at a distance of a few cm from the mouth. The change takes place more rapidly the higher the frequency. According to the results of the experiments at a frequency of 400 and upwards, the wave-front at 5 cm from the mouth of the tube had become sufficiently spherical to obey the law of variation of air velocity with radius within the limits of experimental error. This was the case with or without a large flange on the end of the resonator tube.

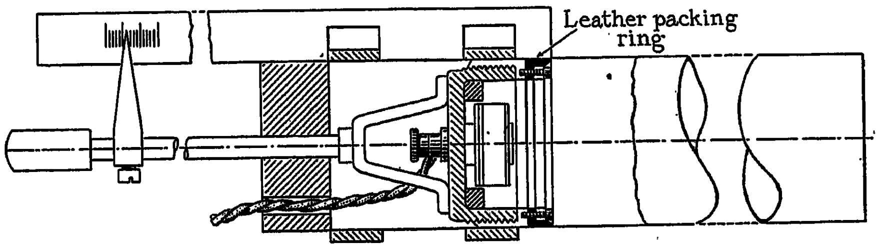

FIG. 14.—Resonator tube and telephone. Scale about half size.

A tube of uniform bore, open at one end and closed at the other, resonates to a fundamental frequency the wave-length of which is about 4 times the length of the tube. The natural overtones of such a tube form an odd series, and if the tube is wide these resonant frequencies will vary considerably from the harmonic series of the fundamental. Such a tube is almost ideal for purifying the sound emitted from a telephone receiver inserted into the closed end of the tube. The second harmonic, if present in the vibration of the telephone diaphragm, will not be reinforced by the tube, and its intensity will fall into insignificance compared with the fundamental. The odd harmonics will be but slightly reinforced by the tube, due to the departure of its natural overtones from the harmonic series.

Such a resonator tube was made of drawn brass 5 cm in diameter and 120 cm long. A telephone of 60 ohms resistance, mounted on a long brass rod, slides within the tube. The sliding fit is rendered perfectly airtight by a greased leather packing ring as shown in Fig. 14. A pointer fixed to the telephone rod indicates the length of the air column on a scale fixed to the tube.

The resonator tube was mounted in the wall of the sound-absorbing chamber; readings were then taken of the variation of air velocity with the telephone receiver current. The relation was found to be a linear one for any frequency (up to 3 000) and length of tube (see Fig. 15).

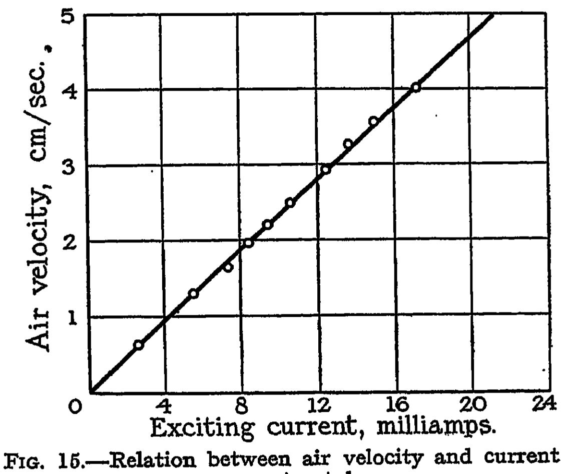

FIG. 15.—Relation between air velocity and current in resonator tube.

For a diverging spherical wave the velocity potential is given by

$$\Phi = \frac{A}{4\pi r}\cos\omega\left(t - \frac{r}{c}\right)^{*}.$$

* *Vide* LAMB: "Dynamical Theory of Sound," chap. 8.

where Φ = velocity potential,
r = radius from the imaginary point source,
c = velocity of propagation of sound in the medium, and
A = a constant.

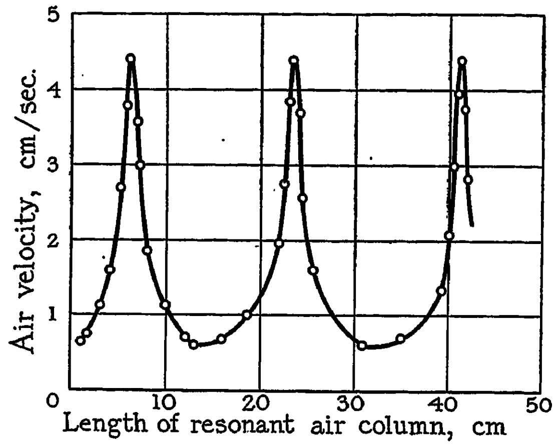

FIG. 16.—Relation between air velocity and length of air column in resonator tube. Frequency = 940 cycles per sec.

The air velocity v is therefore given by

$$v = -\frac{\partial\Phi}{\partial r} = -\frac{A}{4\pi r}\cdot\frac{\omega}{c}\sin\omega\left(t-\frac{r}{c}\right) + \frac{A}{4\pi r^2}\cos\omega\left(t-\frac{r}{c}\right)$$

$$= \frac{A}{4\pi}\left\{-\frac{1}{r}\cdot\frac{\omega}{c}\sin\omega\left(t-\frac{r}{c}\right) + \frac{1}{r^2}\cos\omega\left(t-\frac{r}{c}\right)\right\}$$

$$\therefore \text{R.M.S. velocity } V = \frac{A}{4\pi\sqrt{2}}\sqrt{\left(\frac{1}{r^2}\cdot\frac{\omega^2}{c^2}+\frac{1}{r^4}\right)} \quad . \quad (1)$$

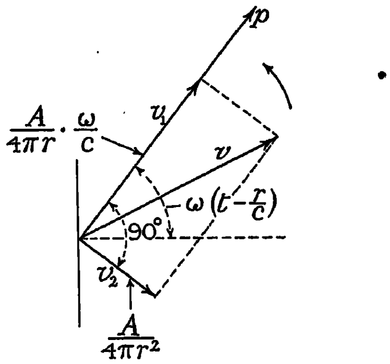

FIG. 17.

The alternating pressure

$$p = \frac{\partial\Phi}{\partial t} = -\frac{A\rho}{4\pi r}\,\omega\sin\omega\left(t-\frac{r}{c}\right) \quad . \quad . \quad (2)$$

and the R.M.S. pressure

$$p = \frac{A\rho\omega}{4\pi r\sqrt{2}}$$

These results are shown vectorially in Fig. 17.

The velocity component v_2 which varies as $1/r^2$ is 90° out of phase with the component varying as $1/r$, and the latter is in phase with the pressure. The sound intensity at the radius r is represented by the product of the pressure and the in-phase velocity component.

Table 6 and Figs. 18 and 18 (a) show the experimental verification of the equation

$$V = \frac{A}{4\pi\sqrt{2}}\sqrt{\left(\frac{1}{r^2}\cdot\frac{\omega^2}{c^2}+\frac{1}{r^4}\right)}$$

In the table the distance r is measured from the mouth of the tube, and it will be seen that it is the radius of the spherical wave, or, in other words, the centre of the wave is exactly at the mouth of the tube.

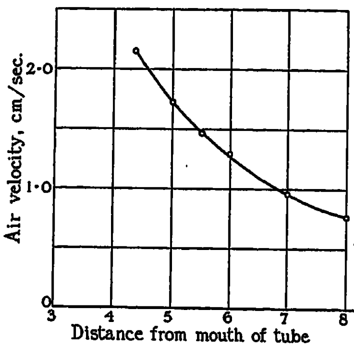

FIG. 18.

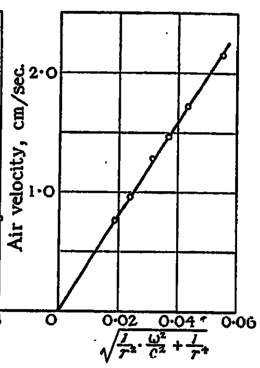

FIG. 18 (a).

The good agreement of the above results with theory, shows that reflection within the sound chamber is negligible, at least within 15 cm from the source.

Similar results were obtained at a number of different frequencies.

TABLE 6.

f = 439; c (at 15° C.) = $3\cdot40 \times 10^4$ cm/sec.
ω = 2750; ω/c = 0·084; current = 3·8 mA.

Distance r	Air velocity V	$\frac{1}{r^2}\cdot\frac{\omega^2}{c^2}$	$\frac{1}{r^4}$	$\sqrt{\left(\frac{1}{r^2}\cdot\frac{\omega^2}{c^2}+\frac{1}{r^4}\right)}$
cm	cm/sec.			
4·38	2·15	0·000368	0·00271	0·0555
5·00	1·72	0·000282	0·00160	0·0434
5·50	1·46	0·000233	0·00109	0·0364
6·00	1·29	0·000196	0·000770	0·0311
7·00	0·96	0·000144	0·000415	0·0236
8·00	0·77	0·000110	0·000245	0·0188

Slope of line = 38·4

$$\therefore v = 38\cdot4\sqrt{\left(\frac{1}{r^2}\cdot\frac{\omega^2}{c^2}+\frac{1}{r^4}\right)}$$

The values of the air velocity V are plotted against the distance r from the mouth in Fig. 18, and in Fig. 18 (a) against the value of $\sqrt{\left(\frac{1}{r^2}\cdot\frac{\omega^2}{c^2}+\frac{1}{r^4}\right)}$.

(7) SOUND-PRESSURE EXPLORER.

The Rayleigh disc was not sufficiently sensitive to measure the sound velocities a few cm in front of a receiver diaphragm at frequencies removed from resonance, and it does not lend itself readily to mapping out the velocities in an acoustic field. Another instrument for this purpose was required. It is essential that the introduction of the instrument should in no way affect the pressure distribution, and that its reaction upon the source should be negligible.

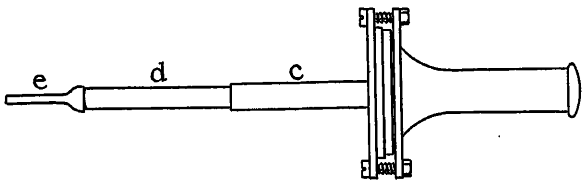

FIG. 19.—Sound-pressure explorer.

With the above requirements in view the device shown in Fig. 19 was constructed. The apparatus consists of an electromagnetic telephone, the diaphragm of which is coupled to the external atmosphere through the system of tubes "c," "d" and "e." The mouth of the tube "e" is introduced into the sound field. The long length of tube was in order to have the mouth "e", as far as possible from the disturbing presence of the telephone upon the sound waves. The telephone and the tube "c" were coated with a layer of cotton waste to reduce reflection, while tubes "e" and "d" were coated with petroleum jelly.

The cross-sectional area of the mouth of the tube "e" is $0 \cdot 12\ \mathrm{cm}^2$, hence the energy abstracted from the sound waves is very small, resulting in small induced E.M.F.'s in the telephone windings. These small E.M.F.'s were increased by a three-stage transformer-coupled valve amplifier in order that the response could be conveniently read upon a valve voltmeter.

DESCRIPTION OF AMPLIFIER AND VALVE VOLTMETER.

Stray alternating electrostatic and magnetic fields had to be guarded against with great care, due to the proximity of heavy electrical machinery and valve oscillators. The flexible leads from the exploring telephone consisted of twin workshop cable armoured with stranded copper. This armouring acted as an excellent screen against alternating electrostatic fields; without such protection the latter were very troublesome. All metal work on the search telephone was connected to the armouring and, hence, to earth. Fig. 20 gives a diagram of connections. The first transformer primary had a resistance of 50 ohms, the secondary a resistance of 5 000 ohms shunted by a 10 000-ohm resistance arranged as a potentiometer. The valves were of the ordinary R type with an anode voltage of 120, 4 volts on the filaments and $1 \cdot 5$ volts negative on the grids. The intervalve transformer had a step-up ratio of 1/2. The whole amplifier except the first transformer was placed in an earthed iron box. It was found necessary to place the first transformer in a separate iron box to prevent the amplifier oscillating.

The voltage on the secondary of the last transformer was read on a valve voltmeter. The valve used for the voltmeter was a Marconi R-type dull-emitter, anode voltage 20 and grid potential $4 \cdot 5$ volts negative. The galvanometer was a 500-ohm Paul unipivot moving-coil instrument giving a maximum scale deflection with 6 μA. This was provided with a variable shunt in order to increase the range. Up to $4 \cdot 8$ volts there is no appreciable grid current; beyond $5 \cdot 5$ volts, however, the grid current rises rapidly. It is essential that the voltmeter should take no grid current from the amplifier transformer, otherwise the voltage-drop would be considerable, resulting in a departure from the direct proportionality between the input and the output amplifier voltages.

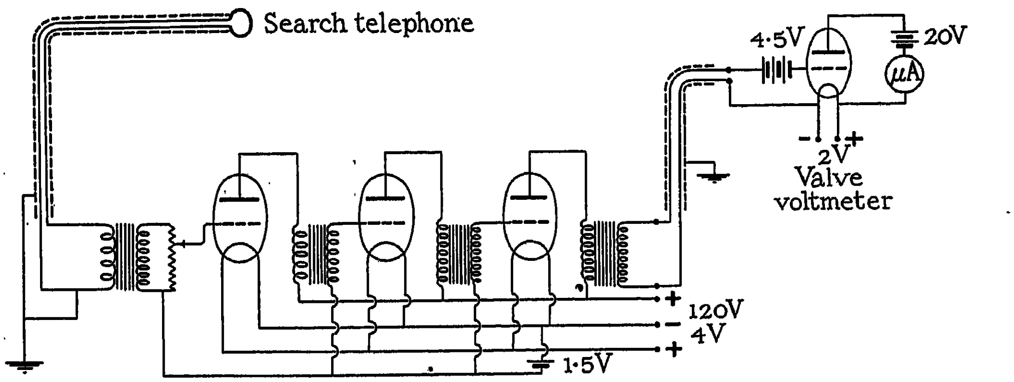

FIG. 20.—Diagram of amplifier.

The calibration of the explorer was carried out with the resonator tube and Rayleigh disc in the sound-absorbing chamber. The disc and the mouth of the explorer were mounted side by side and the distance of the mouth of the resonator tube—i.e. the distance r of the source of sound—was varied.

Table 7 gives the results obtained at a frequency of 694. Col. 1 gives the distance of the source in cm, col. 2 the air velocity as measured by the disc, and col. 3 the amplified explorer voltage e. Col. 5 gives the ratio air velocity$\Big/\sqrt{\left(\frac{1}{r^2}\cdot\frac{\omega^2}{c^2}+\frac{1}{r^4}\right)}$, and shows that the resonator tube is acting as a point source, while in col. 4 is

TABLE 7.

Current in Resonator Telephone 3·8 *mA ; Voltmeter Shunt* 420 *ohms ; Amplifier Shunt* 70 *ohms ; Frequency* 694 *cycles/sec.*

Distance r	Air velocity	Amplifier voltage e	re	$A' = \dfrac{V}{\sqrt{\left(\frac{1}{r^2}\cdot\frac{\omega^2}{c^2}+\frac{1}{r^4}\right)}}$
cm	cm/sec.	volts		
4·20	1·58	1·630	7·00	24·5
5·25	1·13	1·340	7·05	25·6
6·50	0·76	1·075	7·00	24·4
6·60	0·74	1·058	7·00	24·4
7·00	0·67	1·020	7·15	24·2
10·10	0·39	0·700	7·06	24·0
			7·04	24·5

entered the product re of the distance and the amplified voltage. The fact that re is constant indicates that the explorer is measuring pressures, and that the reading of the voltmeter is directly proportional to the pressure of the sound wave at the mouth of the explorer.

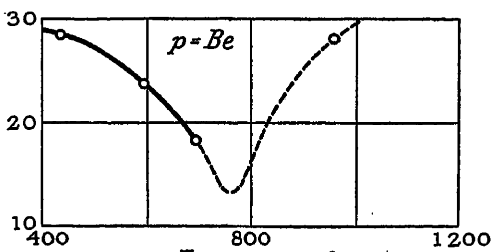

FIG. 21.

We have seen that in a spherical wave

$$V\ (\text{R.M.S.}) = \frac{A}{4\pi\sqrt{2}}\sqrt{\left(\frac{1}{r^2}\cdot\frac{\omega^2}{c^2}+\frac{1}{r^4}\right)}$$

and $$p\ (\text{R.M.S.}) = \frac{A\omega\rho}{4\pi r\sqrt{2}}$$

The average of col. 5 is 24·5, and this is the value of $\dfrac{A}{4\pi\sqrt{2}} = \dfrac{pr}{\omega\rho}$.

And since $re = 7\cdot04$ from col. 4, we have

$$p = \frac{A}{4\pi\sqrt{2}}\cdot\frac{\omega\rho}{7\cdot04}e$$

$$= 24\cdot5 \times \frac{694 \times 2\pi \times 0\cdot0012}{7\cdot04}e$$

$$= 18\cdot2\,e$$

for the calibration of the pressure explorer at this frequency. Writing $p = Be$, the values of B found in this way at frequencies of 439, 590, 694 and 960 are entered in Table 8 and shown graphically in Fig. 21.

These values are used in the efficiency determination described later.

In the neighbourhood of 790 cycles, which was the resonant frequency of the explorer telephone, the latter fails to give a measure of the pressure, since the values of re no longer come constant. At 790 cycles it was found that $(r + 4)e$ was a constant, while the values of $V\Big/\sqrt{\left(\frac{1}{r^2}\cdot\frac{\omega^2}{c^2}+\frac{1}{r^4}\right)}$ were constant as before. This phenomenon was not further investigated, but the use of the explorer at frequencies near 790 was avoided.

TABLE 8.

f	$\dfrac{A}{4\pi\sqrt{2}}$	re	B
439	51·10	5·95	28·5
590	37·4	7·07	23·6
694	24·5	7·04	18·2
960	46·3	11·92	28·1

(8) THE DIRECT MEASUREMENT OF THE ACOUSTICAL-ELECTRICAL EFFICIENCY OF A STANDARD DOUBLE-POLE TELEPHONE.

Before the efficiency of the telephone could be determined by the sound-pressure explorer, the shape of the wave-front of the sound proceeding from the telephone had to be determined.

To simplify as far as possible the contour of the wave-front, a flange was fitted to the telephone and the diaphragm placed 1·1 cm from the plane of the flange, as shown in Fig. 22. The telephone was mounted with

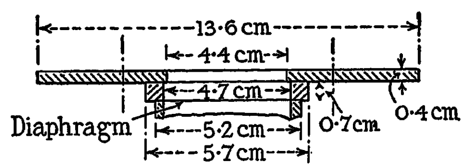

FIG. 22.—Telephone flange.

the plane of the flange vertical, on a piece of apparatus capable of rotating 180° about the centre of the mouth of the flange. The search tube "e" of the sound explorer was placed in front of the telephone, in the horizontal plane passing through the centre of the telephone diaphragm and at a convenient radius from the centre of the flange mouth. The semicircular horizontal arc about the flange mouth could thus be explored by rotating the telephone, the search tube remaining fixed, and its exact position read off on a scale graduated in degrees. It was found that the angle which the search tube made with the wave-front did not affect the reading. The current in the receiver was always kept below that value at which the second harmonic in the sound wave, as tested by means of a Helmholtz resonator, became appreciable.

Table 9 shows the results of pressure explorations with the above apparatus. With a radius greater than 4 cm for any frequency above 400 the pressure is uniform along the 180° arc, indicating that the wave-front has

at this radius become spherical. The higher the frequency the more quickly does the wave-front become spherical. In the determination of the sound-energy output, one measurement only need be made with the pressure explorer, for the flanged telephone may be considered to be a point source sending out hemispherical waves the centre of which lies at the mouth of the flange.

TABLE 9.

Sound-Pressure Explorations around Telephone. Frequency 439 *cycles/sec.*

Position of explorer along 180° arc	Explorer response at radius of :—			
	2·4 cm	3·2 cm	4·0 cm	6·0 cm
degrees	volt	volt	volt	volt
10	1·01	0·720	0·460	0·308
25	0·95	0·711	0·460	0·308
40	0·90	0·705	0·460	0·308
55	0·86	0·695	0·460	0·308
70	0·83	0·690	0·460	0·308
85	0·800	0·682	0·460	0·308
90	0·79	0·680	0·460	0·308
95	0·80	0·682	0·460	0·308
110	0·83	0·690	0·460	0·308
125	0·86	0·694	0·460	0·308
140	0·90	0·705	0·460	0·308
155	0·95	0·711	0·460	0·308
170	1·01	0·719	0·460	0·308

The power may therefore be obtained, since the value of the source A will be known from the pressure determination. The electrical power absorbed by the telephone was determined with the aid of the valve voltmeter previously described and a Duddell thermo-ammeter. The power factor was determined by the three-voltmeter method.* This method of measuring

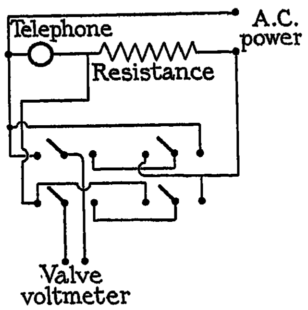

FIG. 23.

small powers is very liable to error unless the readings are very accurately taken with no absorption of power by the measuring instruments. The valve voltmeter was therefore given a sufficiently negative grid potential and a high anode voltage, so that no grid current was taken for voltages up to 5·5.

* A valve voltmeter was used with the switching arrangement shown in Fig. 23.

The results of the efficiency tests may be divided into two parts: (A) in which the Rayleigh disc was used to measure the sound energy, and (B) in which the pressure explorer was used. All the results are collected in Table 10. Method (A) was used for the frequencies near resonance, i.e. for 790, 840 and 885, while (B) was used where the sound intensities were much smaller, at frequencies of 439, 590, 694 and 960. Col. 1 gives the frequency and col. 2 the distance of the sound-measuring device from the flange of the receiver, i.e. from the apparent point source as indicated in Table 9. In col. 3 is entered the sound velocity V as measured by the Rayleigh disc in the (A) series, and the voltage e of the pressure explorer in the (B) series. In cols. 4, 5 and 6 are the voltages V_1, V_2, V_3 across the non-inductive resistance R, the telephone, and the two in series, and in col. 7 is the value of the non-inductive resistance R. In col. 8 is entered the electrical power input calculated from cols. 4, 5, 6 and 7, and as

$$P = \frac{1}{2R}\{V_3^2 - V_1^2 - V_2^2\}$$

In col. 9 for the (B) series is entered the pressure constant B from Table 8.

The velocity at any point of a spherical wave is given by

$$v = \frac{A}{4\pi}\left\{-\frac{1}{r}\cdot\frac{\omega}{c}\sin\omega\left(t-\frac{r}{c}\right)+\frac{1}{r^2}\cos\omega\left(t-\frac{r}{c}\right)\right\}$$

and the pressure by

$$p = -\frac{A\rho\omega}{4\pi r}\sin\omega\left(t-\frac{r}{c}\right) \quad \text{(see Section 6)}$$

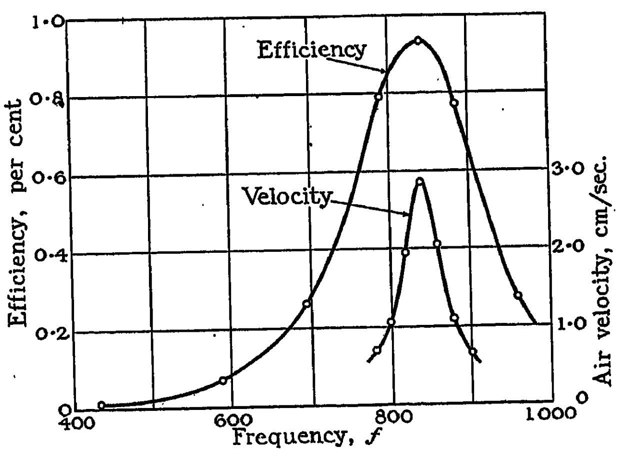

FIG. 24.

and the instantaneous flux of energy across each square centimetre of the sphere is given by the product of these two, and the average flux by the mean of the product or by

$$\frac{1}{2}\cdot\frac{A^2\rho}{16\pi^2}\cdot\frac{1}{r^2}\cdot\frac{\omega^2}{c}$$

The total flux of energy over the hemisphere is therefore

this quantity multiplied by the area of the hemisphere, $2\pi r^2$, and is

$$W = \frac{A^2 \rho \omega^2}{16\pi c}$$

and this is the sound energy output of the telephone receiver, given in ergs/sec. if C.G.S. units are employed throughout.

In the (A) series of results where we measure the R.M.S. sound velocity V, we have for the determination of A the expression

$$V = \frac{A}{4\pi\sqrt{2}}\sqrt{\left(\frac{1}{r^2}\cdot\frac{\omega^2}{c^2}+\frac{1}{r^4}\right)}$$

and hence $$W = \frac{2\pi r^2 B^2 e^2}{\rho c} \text{ ergs/sec.}$$

B is determined from Table 8 and the calculated value of W is entered in col. 10.

In col. 11 is entered the overall acoustical-electrical efficiency, given as $W/(P \times 10^7) \times 100$ per cent (P in watts is multiplied by 10^7 to bring it to ergs/sec.) i.e.

$$\frac{W}{P} \times 10^{-5} \text{ per cent.}$$

These values of the efficiency are plotted in Fig. 24 against the frequency, and there is also plotted for comparison the resonance curve of the receiver diaphragm, which has a decay factor of 125.

TABLE 10.

	1	2	3	4	5	6	7	8	9	10	11
	f	r	V	V_1	V_2	V_3	R	P	B	W	Efficiency $\frac{W}{P} \times 10^{-5}$
		cm	cm/sec.	volts	volts	volts	ohms	watts		ergs/sec.	per cent
(A)	790	3·6	1·44	1·98	2·41	4·09	200	0·0172	—	1 360	0·79
	840	3·6	1·45	1·94	2·20	3·93	200	0·0175	—	1 640	0·936
	885	3·6	1·42	2·02	2·56	4·40	200	0·0237	—	1 830	0·772
			e volts								
(B)	439	4·28	0·210	6·42	2·85	9·25	200	0·0915	28·5	100	0·011
	590	4·28	0·215	1·94	1·67	3·28	200	0·0108	23·6	72·5	0·067
	694	4·28	0·652	2·06	1·96	3·76	200	0·0152	18·2	395	0·26
	960	4·28	0·352	1·80	1·443	3·045	237	0·00988	28·1	275	0·278

Hence

$$W = \frac{2\pi\omega^2\rho}{c}\cdot\frac{V^2}{\left(\frac{1}{r^2}\cdot\frac{\omega^2}{c^2}+\frac{1}{r^4}\right)} \text{ ergs/sec.}$$

and this value is entered in col. 10, taking $\rho = 0{\cdot}0012$ g/cm^3 and $c = 34\,000$ cm/sec.

In the (B) series we have

$$p = Be = \frac{A\omega\rho}{4\pi r\sqrt{2}}$$

The value of the efficiency at resonance—about 1 per cent—is just about what is generally accepted to be the figure for a standard receiver, but as far as the authors are aware no direct measurement has previously been made.

The whole of the experimental work was carried out in the Telegraphy and Telephony Laboratories, at the City and Guilds (Engineering) College, South Kensington, where the authors have had the privilege of discussing their results with Prof. C. L. Fortescue, O.B.E.

WORLD-WIDE RADIO TELEGRAPHY.

By Professor G. W. O. Howe, D.Sc., Member.

(Abstract *of* Faraday Lecture *delivered before the* North-Eastern Centre *17th December,* 1924; *also before the* North-Western Centre *6th January, before the* North Midland Centre *27th January, before the* South Midland Centre *28th January, and before the* Scottish Centre *17th February,* 1925.)

I wish in the first place to take you back in imagination a hundred years and trace the evolution of the conception of electromagnetic waves, their experimental realization, and their ultimate application to world-wide radio telegraphy and telephony.

At the beginning of last century three apparently independent phenomena were known to scientists, viz. the attraction and repulsion between magnet poles, the attraction and repulsion between electric charges, and the production of an electric current by means of a voltaic cell. It is only just over a hundred years ago that Oersted discovered the connection between the magnetic and the electric effects. It was Faraday who, seeking a physical explanation rather than a mathematical expression of the forces, investigated the phenomena in the medium and formulated his conceptions of the magnetic and electric fields with their lines or tubes of force. It was in the sixties that James Clerk Maxwell conceived and developed his electromagnetic theory, one of the greatest achievements of the human intellect. By analogy from the propagation of pulses or waves through a material medium, depending on its density and elasticity, he predicted that electromagnetic waves should travel through space at a speed depending on its magnetic and electric properties, and calculation gave this speed as 300 000 km per second, which was exactly the speed at which experiment had shown light to travel. The obvious inference that light is an electromagnetic phenomenon has been amply corroborated.

It was in 1888 that Hertz succeeded in producing electromagnetic waves in space by purely electrical methods, but it was not until 1895, 18 months after the untimely death of Hertz, that Marconi commenced his experiments with the definite object of using the Hertzian waves for the purpose of telegraphy, and it is largely due to his prophetic foresight, courage and perseverance that we owe the rapid development of radio telegraphy in those early days. By 1899 he had established communication across the English Channel, using single masts 150 ft. high. The transmitters consisted of Ruhmkorff coils and Leyden jars, the receivers of coherers and morse inkers. Thus encouraged, Marconi decided to attempt communication across the Atlantic and made preliminary tests in 1901 with a power of about 10 kW. The report that signals had been heard over such a distance was received with some incredulity, which was not surprising in view of the improbability of such an achievement. The waves were known to be of the same character as light, to travel in straight lines and to be unable to penetrate far into the earth. Why then should they bend round the curvature of the earth and arrive in America, which is separated from Cornwall by a mountain of sea water 200 miles high? Mathematical investigation has shown that these doubts were well founded—or rather, would have been well founded had it not been for some mysterious agency, up to that time unsuspected, which introduced a new factor into the problem. Signals were undoubtedly received and this led to the completion of the stations at Poldhu and Cape Cod, Clifden and Glace Bay, and thus to the inauguration of a trans-oceanic wireless service.

Although it is now over 20 years since the discovery that the electromagnetic waves employed in radio telegraphy bend around the earth, the exact nature of the beneficent agency is still a matter of discussion, but it is now generally agreed that the cause lies in the upper atmosphere being to some extent conducting due to the presence of free electrons or ions. This suggestion was put forward about the same time by Prof. Kennelly of Harvard and by Oliver Heaviside, and the postulated layer of conducting rarefied gas is known as the Heaviside layer. The idea of reflection at the lower surface of such a layer has been generally abandoned in favour of the alternative theory that the waves are refracted or bent downwards by passing through the conducting stratum. There are many peculiarities in the transmission of wireless signals which compel us to look to the upper atmosphere for an explanation, and it is interesting to note that meteorologists have made somewhat similar assumptions as to the conductivity of the upper atmosphere to explain the causes of the diurnal variation of the earth's magnetism.

To send out waves, it is necessary to produce in the vertical wire of the transmitting aerial an alternating current of very high frequency, and in order that a large current may flow it is necessary to provide at the top a large electrical reservoir or capacity into which the current can flow. This takes the form of a network of wires spread out horizontally. In large stations this may cover a square mile or more, and the masts or towers required to support it are one of the most costly items of the installations. The waves are produced by the rapid starting and stopping of the current in the vertical wire; a very close analogy is the kink transmitted along a stretched cord when the end is suddenly jerked up or down.

The various ways of producing the high-frequency current in the aerial may be divided into those such as the spark, arc, and thermionic valve in which the frequency of the oscillations is determined by the inductances and capacities of circuits, and those in which the frequency is fixed by the speed of an alternator.

All the early development was carried out by means of the spark system, but this method is now obsolete for long-distance transmission. The spark merely acted as an automatic switch which, when the voltage across the condenser had reached a given value, closed a circuit by which the condenser discharged through an inductive coil. The use of the spark in all the early wireless transmitters led to the idea that it was in some way the source of the radiated electromagnetic waves, whereas it was really a very unimportant detail. The fallacy was given the appearance of official sanction in Germany by the adoption of the name Telefunken (Funke = spark) by the leading company; it is being perpetuated by calling the broadcasting service "Rundfunkdienst," a peculiarly misleading designation.

The first competitor with the spark in long-distance communication was the arc converter originally discovered by Duddell but modified and made applicable to radio telegraphy by Poulsen. This method is still employed in a number of high-power stations.

The most modern method of producing the requisite high-frequency current is by means of the three-electrode thermionic valve. In principle this is very similar to the arc method, both devices converting a direct-current supply into an alternating current in an oscillatory circuit. Whereas arcs can be constructed to give an output of 1 000 kW, thermionic valves cannot conveniently be constructed to give more than about 20 kW, and large radiated power is obtained by employing a number of valves in parallel.

The other class of generator is in principle the same as those alternating-current generators in the local power station, in which a magnet wheel is rotated and induces in the stationary winding a current of a frequency determined entirely by the speed of rotation and the number of poles in the machine. Many of the largest wireless stations in the world now employ this method, which must always appeal to the electrical engineer as the ideal method of producing alternating currents. The difficulties of design, however, increase rapidly with the frequency, and alternators can only be constructed on a large scale for frequencies up to about 20 000 cycles per second ($\lambda = 15$ km). At frequencies of 500 000 to 1 000 000 such as are used for ordinary marine work and broadcasting, to say nothing of the frequencies of several millions now being used in the latest short-wave systems, the engineering problems in the design of an efficient a.c. generator become almost insuperable.

The German Telefunken Company favour a method in which the alternator delivers the current at a quarter of the requisite frequency to special transformers which are made dissymmetrical in their operation by means of a direct-current excitation and which consequently give a secondary current having double the primary frequency. By repeating the process the original frequency is quadrupled. This method has the very great advantage of lowering the alternator frequency from about 20 000 to about 5 000 cycles per second.

Reception can be carried out by means of a vertical non-directive aerial, a directive coil aerial, or a long horizontal wire which is also directive in its action.

In all cases the high-frequency oscillations must be rectified, i.e. made more or less unidirectional, in order that they may influence the telephone diaphragm or galvanometer. This is the function of the detector. In all except spark stations and a few special cases, the waves sent out by a telegraph transmitter are continuous so long as the key is held down. Such oscillations, even although rectified, would still be inaudible unless made intermittent in their action on the telephone. This intermittency is generally produced by the interference set up in the receiving circuits between the received oscillations and other oscillations of nearly the same frequency set up by a local oscillator. By altering the frequency of this local oscillator, the rapidity of the "beats" between it and the received oscillations can be adjusted, and the receiving operator can thus adjust the pitch of the note heard in the telephone. This is the so-called heterodyne method of reception.

In modern commercial long-distance radio communication, the transmitting and receiving stations are placed several miles apart, so that the latter can receive from the distant station while the transmitting station is working, without undue interference. They are both controlled and operated from a central office in the city by means of ordinary telegraph lines.

In conclusion, reference may be made to the so-called beam systems in which either by reflectors or by suitably arranged transmitting aerials the radiated energy is sent out in the desired direction, thus greatly increasing the efficiency of the transmission.

[The lecture was illustrated by a large number of lantern slides.]

INSTITUTION NOTES.

Specimens of Mica.

A collection of 90 specimens of mica will be on view in the Institution Library for the next few months. A table is also available showing the classification of the specimens and giving their composition, characteristics, descriptions and trade names.

National Certificates and Diplomas in Electrical Engineering.

The following Institute has been approved under the scheme drawn up by the Board of Education and the Institution:—

Approved for Higher Grade Certificates (Advanced Part-time Course).

Woolwich Polytechnic Institute.

Electrical Appointments Board.

The Board desires to remind members who have applied for registration that the period for the retention of names on the Register is three months from the date of application. If after this period members are still without positions, they should notify the Secretary of the Board who will extend the registration period for a further three months.

Failure to comply with this regulation will be regarded as an indication that members desire their names to be struck off the Register.

Informal Meetings.

The following Informal Meetings have been held :—

65TH INFORMAL MEETING (9TH FEBRUARY, 1925).

Chairman : Mr. A. G. Hilling.

Subject of Discussion : " Broadcasting " (introduced by Capt. P. P. Eckersley).

Speakers : Messrs. C. F. Phillips, J. Coxon, P. Voigt, H. H. Dyer, E. S. Ritter, A. T. Smee, — Mulholland, H. E. Morrish and E. G. Bedford.

66TH INFORMAL MEETING (23RD FEBRUARY, 1925).

Chairman : Mr. H. T. Young.

Subject of Discussion : " The Electric Journals; Past, Present and Future " (introduced by Mr. W. E. Warrilow).

Speakers : Messrs. J. W. Beauchamp, J. F. Shipley, W. Day, E. Kilburn Scott, A. H. Allen, E. S. Ritter, J. Coxon, M. Whitgift, J. R. Bedford, F. H. Masters, W. L. Randell, E. A. Gatehouse, W. A. Moore and H. T. Young.

67TH INFORMAL MEETING (9TH MARCH, 1925).

Chairman : Mr. W. E. Warrilow.

Subject of Discussion : " Illumination " (introduced by Mr. C. W. Sully).

Speakers : Messrs. J. R. Bedford, A. B. Mann, R. J. Hines, W. E. Rogers, J. Coxon, W. A. Erlebach, A. G. Hilling, P. Dunsheath, O.B.E., F. Peake Sexton, A. F. Harmer, A. Collins, M. Whitgift and W. E. Warrilow.

68TH INFORMAL MEETING (23RD MARCH, 1925).

Chairman : Mr. L. J. Gooch.

Subject of Discussion : " Panel Heating " (introduced by Mr. R. Grierson).

Speakers : Messrs. H. T. Young, H. H. Perry, P. Dunsheath, O.B.E., J. Coxon, R. J. Hines, J. R. Bedford, L. M. Jockel, W. A. Ritchie, A. E. Falkus, W. E. Spiers, N. Prentice, C. T. Walrond, W. L. Wreford, F. Pooley, V. Cornelius, F. Tremain, P. S. Davies, D. A. B. Partridge and L. J. Gooch.

69TH INFORMAL MEETING (6TH APRIL, 1925).

Chairman : Lt.-Col. K. Edgcumbe.

Subject of Discussion : " Insulation Problems in High-voltage Engineering " (introduced by Mr. A. Collins).

Speakers : Col. K. S. Maxwell, Messrs. Duncan, H. C. Silver, P. Dunsheath, O.B.E., J. F. Shipley, S. Messent, H. F. Quinton, A. Berkeley, W. A. Erlebach, R. T. Fleming, E. S. Ritter and Col. K. Edgcumbe.

70TH INFORMAL MEETING (20TH APRIL, 1925).

Chairman : Mr. W. E. Warrilow.

Subject of Discussion : " Latter-day Wireless " (introduced by Mr. M. Hart).

Speakers : Messrs. A. F. Harmer, H. E. Morrish, P. W. Willans, T. McGrath, H. Brown, J. Coxon, E. W. Moss, W. Day, A. E. Lee, E. W. Braendle, W. A. Erlebach, A. G. Hilling, H. H. Easter and W. E. Warrilow.

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 March–25 April, 1925 :—

	£	s.	d.
Allen, C. W. (Liverpool)		5	0
Banner, E. H. W. (Wembley)		5	0
Barton, T. (Wigan)		2	6
Baynham, H. P. (Carlisle)		5	0
Berindei, M. (London)		10	0
Bowden, J. R. J. (London)		5	0
Brierly, R. F. H. (Newcastle-on-Tyne)		3	6
Brooks, R. (Ashton-on-Mersey)		5	0
Brown, J. (Edinburgh)		5	0
Burbridge, P. G. H. (Twickenham)		5	0
Burgess, P. J. (Birmingham)		5	0
Burgum, W. T. (Brazil)	1	0	0
Bust, F. H. (Lynn, Mass.)	1	0	0
Carpenter, G. W. (Scarborough)		5	0
Cartwright, C. L. (Madras)	1	0	0
Clarke, A. E. (Manchester)	1	1	0
Craig, J. L. W. (Battlesbridge)		5	0
Cramer, D. H. (London)		5	0
Crowther, L. H. (Sheffield)		5	0
Davis, P. K. (Blackburn)		3	6
De Renzi, A. J. C. (Newcastle, Staffs.)		10	6
Dibben, E. (Manchester)		5	0
Eccleston, R. J. (Liverpool)		8	6
Ellis, C. J. A. (Bournemouth)	1	1	0

	£	s.	d.
Ferguson, J. R. B. (Kew Gardens)		5	0
Field, H. (Swansea)		2	6
Forbes, L. J. B. (Doncaster)		10	0
Fox, P. S. (Southend-on-Sea)		5	0
Freeman, J. G. (London)	1	1	0
Gibbard, H. E. (Banbury)		5	0*
Ginno, S. C. (Birmingham)		2	6
Grepe, F. Y. (London)		5	0
Grover, E. E. (Hexham-on-Tyne)		7	6
Gunn, J. H. (Birmingham)		2	6*
Harrison, G. E. (Manchester)		3	6
Highfield, J. S. (London)	3	3	0
Hill, S. F. (London)		5	0
Horsfall, L. A. (Leicester)		10	0
Hudson, J. B. (Leigh, Lancs.)		15	0
Hughes, E. (Brighton)		5	0
Hunter, G. (Gateshead-on-Tyne)		2	6
Informal Meetings Smoking Concert (per J. F. Avila)		14	8
Jewell, C. J. (Norwich)		15	0
Johnson, F. H. (Ipswich)		8	6
Johnson, J. R. (Widnes)		10	0
Kehoe, H. (Bury)		2	0
Kelso, J. C. (Glasgow)		5	0
Kirby, C. C. (Gloucester)		3	6*
Lea, W. H. (Manchester)		10	0
Le Clezio, M. J. L. (Mauritius)		6	0
Lisle, G. S. (Gateshead-on-Tyne)		5	0
Lister, J. F. (Birmingham)	1	1	0*
Lockett, T. H. (London)		3	6
Lumby, F. (Oldham)		2	6
Lunn, A. L. (Manchester)		10	6
McKellar, D. J. (Glasgow)		10	0
Macleod, D. M. (Glasgow)	1	1	0
Maidman, F. W. (Nigeria)		10	0
Maxfield, G. W. (Blackburn)		4	0
Mead, R. H. (London)		5	0
Miller, N. H. (London)		10	0
Moore, D. (London)		8	6
Morris, A. J. (London)		3	6
Munro, H. D. (Exeter)		10	0
Nagabushanam, S. (Tanjore, S. India)		10	0
Orrell, W. (Lostock, Lancs.)		2	6
Pettit, C. G. (Birmingham)		5	0
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ELECTRICITY IN MINES.

By Major E. IVOR DAVID, Member.

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SUMMARY.

The mining industry is one of the largest producers and users of electric power in this country. It is generally assumed that the methods of production and utilization are not as economical as they might be. The following notes of some efforts to achieve efficiency and increase reliability, together with results of tests made with this end in view, may be of general interest.

For the purpose of reference the paper is divided into three parts:—

Part 1 deals with the general problem of power production at mines, giving briefly the essential differences between a colliery power plant and a normal power plant.

Part 2 deals with the modern methods of supplying the four main power-consuming units at mines, with particular reference in each case to the question of the utilization of synchronous motors, and also discusses the advantages and disadvantages of alternating-current and Ward-Leonard control for electric winders.

Part 3 gives the results of progressive conversion of several mines from steam to electric drive for the various main units and also the effect of supplying compressed-air power from a central station in a similar way to electric power.

Part 1.

Dealing first with the generation of power, it is of interest to note that the first high-pressure high-temperature station of moderate size in this country, and possibly in the world, to operate continuously was installed in connection with a group of collieries.

A colliery power station should be capable of dealing with all classes of fuel which from time to time are not marketable. These will mostly be the lower grades, and the boiler plant should therefore have ample grate area and draught capacity and proper furnace construction for the economical combustion of these fuels. The utilization of coke-oven gas is a difficult problem. Gas engines have higher thermodynamic efficiency but higher maintenance cost, poor flexibility and reliability. These have all to be weighed against their one advantage. Compared with modern high-efficiency turbine plants the margin of thermodynamic efficiency in their favour is small, and in most cases it is a better commercial proposition to burn the gas under boilers.

Table 1 gives a comparison of the cost per electrical unit for the two methods of utilization. The gas-engine units are of the 1 600-kW low-speed 4-cylinder type, and the steam plant is a 350 lb./sq. in., 700° F. installation, the gas being used to supplement coal-firing in 35 000-lb. boiler units. The test efficiency when coal-fired was 87 per cent, and the daily efficiency 80 to 82 per cent, so that an efficiency of 85 per cent for gas-firing is reasonable.

The gas-engine figures are based on an output of 16 million units per annum. The new gas engines are fitted with waste-heat recuperator boilers. The gas- and coal-fired steam stations are based on an output of 150 million units per annum.

The disposal of coke breeze and coke ashes has also to be provided for. A system of blanketing with medium volatile coal has proved a satisfactory method of burning them. Low-grade fuels should be washed if the ash content exceeds 10 per cent, but a minimum of 5 to 6 per cent ash is quite low enough.

The high capital cost of extra-high-pressure and extra-high-temperature steam, combined with the attendant fuel-saving devices such as evaporators, feed-water heaters fed with bled steam, air-heaters, etc., hardly seems justified with cheap fuel delivered direct to the boilers free of railway charges, but in some collieries where all fuel raised has a fairly high value, high capital expenditure may be justified.

Boiler efficiencies of 70 to 75 per cent can be maintained with fuel of high calorific value, even in small

TABLE 1.

Coke-Oven Gas Utilization from 150 *Ovens.**

	Old gas engines	New gas engines	Gas-fired boilers	Coal-fired boilers
Wages	16·25	12·95	8·78	8·78
Fuel	41·8	34·4	41·3	46·18
Stores and other charges	23·0	21·8	10·1	10·1
Repairs and renewals not included in stores	15·1	7·8	3·74	3·74
Capital charges	21·8	31·2	31·2	31·2
Expressed as percentage of coal-fired station	117·95	108·15	95·12	100·0
Station thermodynamic efficiency, per cent	19·05	24·0	19·35	16·35

* All values are expressed as percentages of the cost per unit in the coal-fired station.

colliery boiler plants, but efficiencies of this order require constant high-class technical supervision, which can better be concentrated in large central stations. Where fuels are available which cannot be burned on any ordinary stokers, pulverizing is a feasible proposition.

Water for both boiler feed and condensing purposes is one of the great difficulties at most collieries, and at high-pressure stations evaporators are a necessity.

The other problems such as size of generating units, reactance (self-contained or external) of transmission, and substation equipment, etc., are common to all power schemes and have been fully dealt with in recent papers. Switchgear has to be particularly robust and must also not be susceptible to the effect of dust and damp. Compound-filled gear seems to meet most requirements.

Power factor correction has become a pressing need in large power installations. Overhead transmission lines with their comparatively high reactance, high-reactance transformers and, in many cases, busbar and feeder reactances necessary for protection of generating plant and switchgear, have lowered the already bad colliery power factor, resulting in reduced outputs from generating plant and in high voltage-drop in transmission lines, transformers and reactances. Phase-advancers, synchronous and static condensers have all been tried, but the best results have been obtained from synchronous motors driving the larger units.

Salient-pole and cylindrical-rotor types of motors each have their advantages, which have been fully discussed in recent papers before the Institution.* The present author gave comparative figures of various drives in the discussions on these papers and, in the discussion on Kapp's paper, an example of the use of a static condenser, with the results obtained therefrom and suggestions as to where this apparatus is applicable.

Part 2.

The four most important loads to be dealt with at modern collieries are pumping, ventilation, air compressing and winding. The units consumed per ton of coal raised for a modern colliery raising 2 000 tons of coal per day from a depth of 600–700 yards and using compressed air for cutting, conveying, inbye haulages and pumps are given in Table 2.

TABLE 2.

	Units per ton
Winder	4
Fan	3
Compressed air	20
General pit use	$1\frac{1}{2}$
Pumping	$3\frac{1}{2}$
Total	32

These figures apply specifically to South Wales conditions with highly developed compressed-air utilization, and very different figures will be obtained from other districts.

Pumping.—The efficiency and reliability of modern multi-stage turbine pumps, combined with their compact size, make them particularly suitable for use in mines. Up to 150 h.p., squirrel-cage motors are quite satisfactory, particularly those with the Boucherot type of rotor winding which may be switched directly on to the line. Auto-transformers for starting are unsatisfactory and slip-ring motors are preferable above 150 h.p. High power factor and efficiency are obtainable with 4-pole or 2-pole machines of all sizes, and only in exceptional circumstances need synchronous-type induction motors be considered for pump drives.

Fans.—Ventilating fans provide an almost uniform load and are particularly suited for power factor correction. The starting torque required is moderate, but, as it is usual to start fans under load in this country, the synchronizing torque required is high. Salient-pole motors cannot give the required torque, and cylindrical-type rotors are used. Experiments have been carried out in the United States with salient-pole machines using a friction clutch drive and also reducing the starting effort by closing the fan discharge.*

Owing to the moderate speed of mine-ventilating fans it is usual to drive through some type of reduction gear. In the early stages of the development of a mine the quantity of ventilating air is low, the requirements gradually increasing in both volume and pressure as roads lengthen and workings extend. It is sometimes required to reduce the volume and pressure during non-working days. Variable-speed motors were largely used in the early days, but these hardly justified their extra cost and lower efficiency, particularly on low loads. Progressive increases in speed can be arranged in the reduction gear, where this is of the spur and pinion type, by changing the gear wheels. Recently the author introduced the old jockey-pulley drive with modern improvements and this has proved a most efficient and flexible method of speed reduction. To change the fan speed, all that is necessary is to change the motor pulley. Owing to the flat efficiency curve of the synchronous motor at unity power factor, the light-load efficiency is high. A comparison of the efficiencies of a cascade motor and of a synchronous motor is given in Fig. 1.

In addition to the very much higher efficiency at all loads—an important factor in a machine which runs for 8 760 hours per annum—power factor correction can be obtained up to 0·80 leading at full load, and to a still greater extent at lower loads. Further, the initial cost of the variable-speed motor and starting gear is 10–15 per cent higher than that of the synchronous motor. Reduction of ventilation during week-ends or stop-days is a questionable economy. Mining engineers usually prefer to maintain full volume of air to clean out the workings and dilute gas. At one colliery under the author's notice, where a variable-speed d.c. motor-driven fan is installed, the speed has not been varied for three years. Where reduced speed and water gauge are clearly required at week-ends or stop-days, two-speed cascade motors of either the ordinary or synchronous type are giving satisfactory results.

Starting up a 450-kVA synchronous induction-type fan motor on light load (about 90 kW), excited to a

* See, for instance, L. H. A. CARR: "Induction-type Synchronous Motors," *Journal I.E.E.*, 1922, vol. 60, p. 190; also G. KAPP: "Improvement of Power Factor," *ibid.*, 1923, vol. 61, p. 89.

* CRAMER and MACDONALD: *Proceedings of the Association of Iron and Steel Electrical Engineers* [Pittsburg], vol. 4, no. 5.

power factor of about 0·5 leading, improved the power factor of a colliery system from 0·7 to 0·87 or 0·9 and the voltage at the busbars increased from 3 050 to 3 150 volts, with both a.c. winders off.

The Lenix belt drive has some peculiar properties. There is no measurable slip; in fact the speed ratio appears to be proportional to the diameters of the pulleys plus the belt thickness, i.e. the diameters to the neutral axis of the belt. It is very difficult to give accurate figures for the efficiency, but the belt drive appears to be equal, if not superior, to a high-class helical gear reduction.

Another interesting type of synchronous motor for fan drives has a salient-pole rotor with extended pole-tips having a single-phase winding in semi-enclosed slots. The pole windings are split in halves for starting and are connected as a second phase, and a metallic resistance is placed in series with these two windings. The motor starts and has a torque characteristic similar

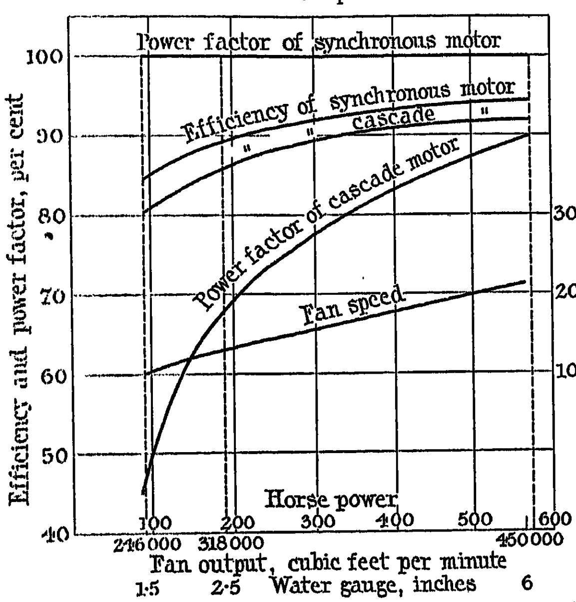


FIG. 1.—Curves of synchronous and cascade motors driving fans.

to that of an ordinary slip-ring machine. The pole-face winding is short-circuited when up to speed and forms an amortisseur. The salient-pole winding is excited in the usual way. Fig. 2 shows the connections. The advantages of this machine over an induction-type synchronous motor are (1) higher efficiency and (2) normal voltage excitation.

Compressed air.—In the gassy seams of the South Wales steam-coal measures there is strong opposition to the use of electricity, whilst every effort is being made to overcome this prejudice and to produce electrical machines which can claim to be absolutely safe under all conditions of operation. In the meantime the mining engineer's demand for compressed air as an operating medium at the working face has to be met, and the low efficiency of machines utilizing compressed air is neutralized as far as possible by higher efficiency in production and distribution.

Compressors.—The high-speed vertical two-stage compressor which is favoured in this country for electric drive was until 1918 thought to be unsuited for direct coupling to salient-pole synchronous motors, and the wound type of rotor with its higher starting torque was considered necessary. Owing to unsatisfactory experiences with this type, the author carried out a series of starting experiments with a large d.c. motor-driven compressor of the horizontal cross-compound type and also with an induction-motor-driven high-speed vertical type, both fitted with unloading devices on the high- and low-pressure cylinders. The cross-compound type took 25 to 30 per cent of full-load torque to start, and the vertical type about the same. In the meantime a salient-pole synchronous motor had been installed in a

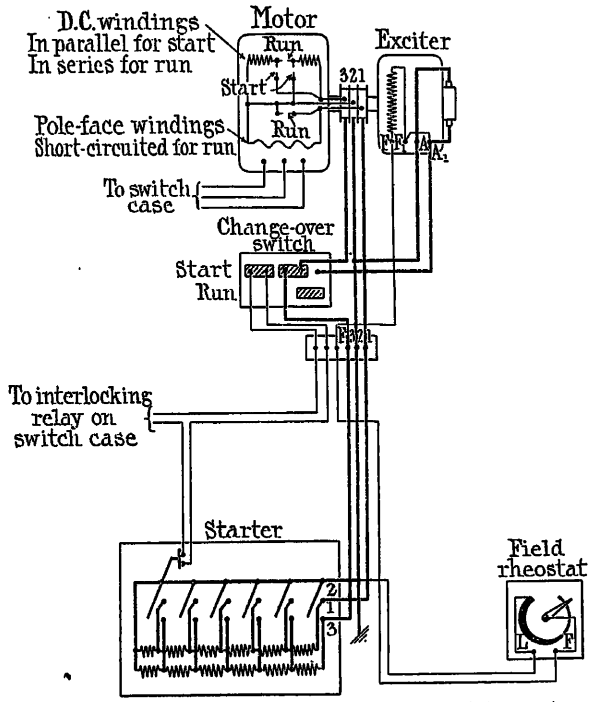


FIG. 2.—Connections of S.G.E. salient-pole, high-starting-torque synchronous motor.

Lancashire colliery to drive a Walker vertical compressor through a friction clutch. It was soon found that the clutch was unnecessary, and two salient-pole motors of 1 125 h.p. at 214 r.p.m. were installed driving vertical two-stage compressors having an output of 6 500 cubic ft. per min. compressed to 75 lb./sq. in. Starting curves of one of these are given in Fig. 3. Slightly more than full-load current is taken at the start and when changing over from tap to full voltage. This is momentary and is carried by the system with a hardly appreciable voltage-drop. Owing to the large air-gap used in this type of motor it was found possible to dispense with the bearing between the compressor flywheel and the rotor, thus reducing the length of the set by 4 ft. compared with a synchronous induction motor of similar horse-power. The efficiency of these motors at full load and unity power factor is 95·7 per cent, a remarkable figure for motors of this size and speed. The corresponding figure for a synchronous induction motor is 93·2 per

cent, a difference of 2·5 per cent in favour of the salient-pole machine.

A comparison between the efficiency of this type of compressor equipment and a large steam-turbine compressor is of interest. These figures are based upon tests made on a Bellis compressor of 6 500 cubic ft. per min. capacity at 75 lb./sq. in. installed at Penallta colliery and were published in *Engineering* (1921, vol. 112, p. 535), but are now corrected for the later type higher-efficiency motor.

Motor compressor—

Actual volume of air compressed (W)
6 396 cubic ft./min. (475 lb./min.)
Speed .. .. 163 r.p.m.
Ratio of compression (89·51/14·57) .. .. 6·17
Isothermal h.p. of compression—

$$\frac{WRT_0 \log P_3/P_2}{33\,000} = \frac{475 \times 53 \cdot 3 \times 528 \times 1 \cdot 818}{33\,000} = 737 \text{ h.p.}$$

where T_0 = mean atmospheric temperature (abs.) at compressor intake,
P_2 = mean atmospheric pressure,
P_3 = mean pressure of air leaving orifice.

Indicated h.p. from diagram 993
Electrical input at 95·7 per cent efficiency
1 110 h.p. (830 kW)
Brake h.p. output of motor 1 061
Isothermal efficiency of compressor, per cent
737/1 061 = 69·5
Isothermal efficiency of compressor and motor, per cent .. .. 737/1 110 = 66·4

back to the power station. To supply 1 110 h.p (830 kW), assuming an alternator efficiency of 95 per cent, requires 872 kW at the turbine coupling. The direct-coupled turbine driving the turbo-compressor has the same steam consumption and for 1 038 h.p. (775 kW) takes 11·2 per cent less steam than the electrically driven unit. The latter has one compensating advantage, i.e. the light-load losses are much lower than those of the turbo-compressor, in the above cases being only 65 kW with zero output. Of this, 6 kW represents work done in compressing the air, 29 kW the mechanical losses in the compressor (the inlet valve being closed and the high-pressure cylinder unloaded), and 30 kW the core losses, excitation, copper losses and friction and windage of the motor. Where the load varies considerably, as in a single colliery, this is an advantage, but when a group of collieries can be supplied from a central station the load is found to be very uniform owing to the diversity factor of the various compressed-air-consuming machines and the receiver effect of large mains. Typical load curves for a colliery compressed-air plant and an electrical plant are given in Fig. 4. Their resemblance is remarkable.

Experience with the synchronous-motor-driven compressors has been satisfactory, but the starting gear has given some trouble. A number of failures occurred in the auto-transformers. All these showed signs of abnormal mechanical stresses, clampings being strained and coils crushed. Excessive burning of the switch contacts also occurred. It was found that the arc drawn out on the starting-switch contacts was maintained for a length of time sufficient to cause a short-circuit

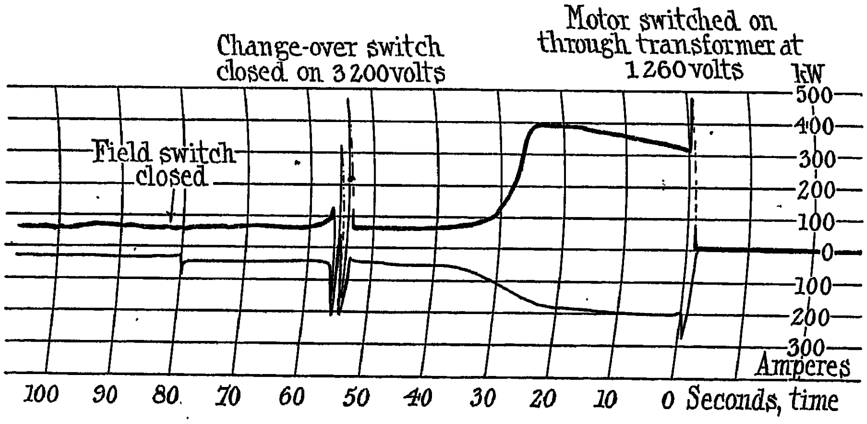


FIG. 3.—Starting curves of 1 125 h.p., 214 r.p.m. synchronous motor.

Steam-turbine-driven compressor (40 000 cubic ft./min. at 75 lb./sq. in.)—

Isothermal efficiency at 75 lb./sq. in. and 40 000 cubic ft./min., per cent .. .. .. 70·8
Equivalent h.p. for 6 396 cubic ft. per min. at 75 lb./sq. in. 1 038
Compared with, for engine and motor, h.p. .. 1 110

The losses in transmission for compressed air and electrical power for distances up to 5 miles are nearly equal.

Ignoring these losses, the comparison can be carried in the circuit formed by the transformer coils, the switch "starting" and "running" contacts, and the connection from the transformer taps to the motor (see Fig. 5). The trouble was overcome first by closing the transformer neutral later and opening it earlier, and secondly by closing the running switch slowly, giving ample time for the arc on the starting contacts to be quenched. Even smoother starting is obtained by the Korndorfer patented method which uses the transformer windings as choking coils. The operations in this method are:—

(1) Switch on transformer with neutral open.
(2) Close tapping switch (this charges the motor through the transformer winding). If the load is very light the motor will start.
(3) Close neutral of transformer. This impresses tapping volts on the motor, which starts or speeds up.
(4) Motor up to speed. Open neutral of transformer. Motor now draws light-load current through the transformer windings so that the choking effect is slight and the motor has nearly full voltage on its terminals.
(5) Close running switch. This short-circuits the transformer windings and impresses full voltage on the motor terminals.
(6) Open tapping switch and starting switch. The transformer is now out of circuit, and the motor is connected to the supply through the running switch only and may be synchronized by closing the field switch.

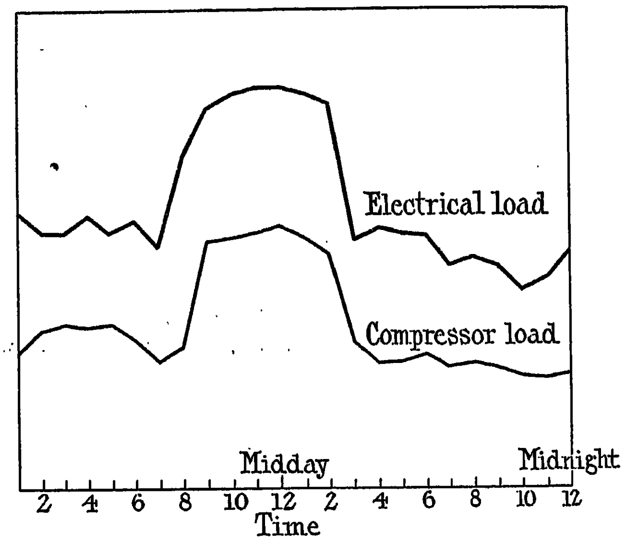


FIG. 4.—Typical load curves for a compressed-air plant and an electrical plant.

Oscillograph records have been taken of these methods of starting, showing the changes of current and voltage. The machine runs up to speed quite smoothly and synchronizes with ease. The whole operation can be carried out by the ordinary unskilled attendant.

Automatic starting and synchronizing by means of a system of contactors appear simple and desirable.

The control of electrically driven compressors is simple. An automatic device controlled by the air pressure closes the inlet valve when the pressure exceeds a predetermined value, and compression ceases, to commence again when the pressure falls by a few pounds per sq. in. and the inlet valve opens and admits air to the low-pressure cylinder.

Electric winders.—The steam winder has been in use for many years and has proved itself reliable and trustworthy, but the electric winder is more efficient, easier to control and easier to maintain in a state of efficiency. Both are equally reliable when of high class and of suitable proportions for their loads.

The case can therefore be settled on running cost so far as the winder is concerned, but the remainder of the plant must influence the choice. If the mine is deep the winder may take anything up to 50 per cent of the total power consumption of the mine. Under these conditions the load on the generating plant is extremely variable and the average load small compared with the peak load. If the plant supplies a single mine, then the diversity factor is low; but if the generating plant supplies a group of mines, then the peaks tend to smooth out and a better diversity factor is obtained. For single deep mines, therefore, electric winding may not be justified, but if the mines can be grouped and either their plants interlinked or power generated at one or more central power stations, the superior economy of the electric winder can be utilized to the fullest advantage.

For shallow mines, particularly where heavy loads can be wound at low speeds, the electric winder is usually two to three times as efficient as the steam winder. Capital charges are slightly higher for electric winders and high-pressure generating plant than for steam-winders and mixed-pressure plant, but the total of running and capital charges is in favour of the electric winder. If power is available at reasonable rates from a reliable supply company, then capital charges will be greatly in favour of electric winding, and the running cost should still be lower than for steam winders.

The chief electrical problem to be solved in a winding equipment is the type of control, i.e. whether it shall be the Ward-Leonard system or an a.c. motor with rheostatic control in the rotor circuit. Secondary problems are those of geared or direct-coupled motors, cylindrical, conical or cylindro-conical drums or Koepe pulleys. Balance ropes have to be considered in the case of cylindrical drums, and are essential with Koepe pulleys. Dealing with the main problem, Stjernberg * gave a mathematical method of analysing electric winding problems and reached a conclusion that if $B = MS/(QT^2)$ exceeded 0·22 Ward-Leonard control was preferable, and indispensable if above 0·3,

where M = equivalent mass reduced to rope = weight in lb. ÷ gravity coefficient,
S = depth of shaft, in feet,
Q = useful load plus friction, in lb.,
T = net time of wind, in seconds.

The expression $B = MS/(QT^2)$ was based on cylindrical drums, with balance ropes, but is equally applicable to cylindro-conical drums, reels, Koepe pulleys or cylindrical drums without balance ropes.

Improvements in the design and manufacture of large double-helical gearing and in a.c. motors since that date have resulted in a.c. winders being permissible for values of B up to 0·25 or even 0·3. In two large a.c. winders recently installed the value of B is 0·292.

* *Journal I.E.E.*, 1911, vol. 46, p. 192.

Another method of deciding on the electrical equipment is to fix limiting values, first for the ratio of the acceleration period T_a to the full-speed period T_f. This ratio should not be greater than 0·5 for reasonable economy for an a.c. motor drive. In addition, the acceleration a should not exceed 4 ft./sec./sec., these figures being actual values in the case of cylindrical drums and average values over the small diameter and scroll for cylindro-conical drums.

If S be the total depth in feet, V the maximum velocity in ft./sec., and T_r the retardation period, which normally equals T_a, we have :—

$$S = V(\tfrac{1}{2}T_a + \tfrac{1}{2}T_r + T_f)$$

Using the ratio of T_a to T_f given above, and $a = r$, we get :—

$$T_a = T_r = \tfrac{1}{4}T, \text{ where } T = T_a + T_r + T_f$$

$$S = 3VT_a = \tfrac{3}{4}VT \,;\; V = aT_a = 4T_a = T$$

$$\therefore S = \tfrac{3}{4}T^2$$

TABLE 3.

Time, T	Depth, S	Velocity	Average velocity, V'
secs.	ft.	ft./sec.	ft./sec.
15	169	15	11·2
20	300	20	15
25	470	25	18·7
30	677	30	22·5
35	920	35	26·2
40	1 200	40	30
50	1 875	50	37·5
60	2 700	60	45

S being the limiting depth from which winding can be economically effected in the time T with maximum velocity V.

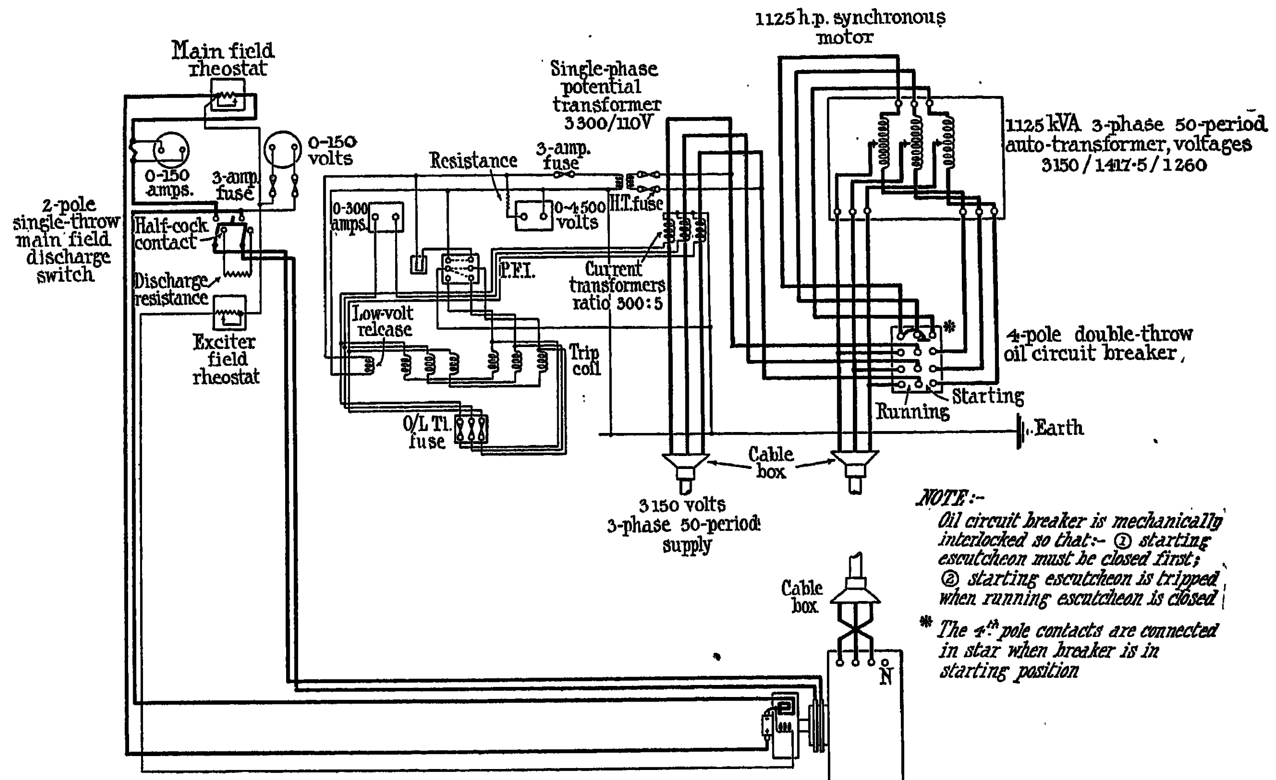
The a.c. motor being inherently a high-speed machine, gearing has been necessary in most cases to transmit the drive from the motor to the drum shaft, the speed of which is seldom higher than 75 r.p.m. or lower than 28 r.p.m. This gearing has in some instances been self-contained with its own bearings, but the two largest a.c. winders in this country at the present time have the spur wheel mounted directly on the drum shaft (which is carried in three bearings) and the pinion coupled to the motor by a flexible coupling of the Bibby type. Fig. 6 shows a normal arrangement for an a.c. winder. Both the double helical and the herring-bone types of gearing have given satisfactory results for some years. Forced lubrication is advisable for the larger sizes.

The speed of the a.c. motor is usually so chosen as to give the lowest energy losses during accelerating and braking. Motors for 250 to 750 h.p. (R.M.S. rating) usually run at 375 r.p.m., 750 h.p. to 1 500 h.p. at 250 r.p.m., and 1 500 h.p. to 2 500 h.p. at 214 r.p.m. The gear ratio, and thus the speed of the drum, can be varied within limits by changing the pinion, but the shaft has to be moved to suit the varying centres. Any large change of drum-speed, therefore, can only be obtained by changing both spur and pinion wheels, and this is an expensive business.

The induction motor is normally a constant-speed machine, its speed variation with short-circuited rotor from no load to full load being only 2 to 5 per cent, but by inserting resistance in the rotor circuit this slip may be increased up to 100 per cent. The speed reduction is proportional to the voltage across the rotor slip-rings, which again is proportional to the torque and resistance in the rotor circuit. Thus the speed corresponding to any particular rotor resistance is not constant, but depends also on the load. Further, regenerative braking in an induction motor is only possible at speeds above synchronism. At any speed below this, to obtain a braking effect the motor must be reversed, and power corresponding to the torque exerted drawn from the line. This power, together with the braking energy absorbed, passes through the rotor to the resistances, and is there dissipated. It is impossible, therefore, to obtain the same delicacy of control as in the Ward-Leonard system.

In high-speed winding, necessary owing to the reduced working hours in mines, retardations of 4·5 and in some cases 6 ft./sec./sec. are necessary to obtain the required output. If normal braking is used, wooden brake blocks last only 4 to 5 weeks and patent fabric linings about double this time. Reverse-current braking is cheaper and more reliable and is used for ordinary coal winding and for lowering men. Regenerative braking is permissible for lowering men for long, slow winds, but reversed current is used to slow down at the ends of the winds. Actually it is safer to use regenerative braking under the above conditions, as it provides a definite limiting speed (5 to 10 per cent above synchronism), rather than to switch off (as is sometimes done) and brake only when the speed becomes excessive. Alternating-current controllers for large motors employ liquid electrolyte, and the resistance is varied in one of two ways; first, moving electrodes; and secondly, moving electrolyte. In the first the resistance is varied by varying the length of liquid electrolyte between fixed and movable electrodes. In the second the resistance is varied by varying the depth of electrolyte in the tank, in which are immersed a number of electrodes. Thus the immersed area is varied, and so the resistance. Each type has its particular advantages. The first lends itself to rapid acceleration, manœuvring and reverse-current braking, the second to uniform acceleration, which can be set for any required rate, and is thus suitable for a fixed and definite rate and load per wind, but it is not so flexible for manœuvring and reverse-current braking. The first method requires the active portion of the electrolyte to be contained in vessels of insulating material. In the second method the electrodes are carried on insulated frames, and the electrolyte in a metal vessel which may be earthed. The electrolyte is circulated constantly by means of a pump, and its height on the electrodes fixed by a movable weir. In

this type there is a danger that when reverse current is quickly applied after a full-speed run the electrodes would be immersed (the liquid not having had time to fall) and, the rotor resistance being low, insufficient torque would be produced in the rotor, resulting in a jerk and damage to the mechanical gear. Again, if the liquid has time to fall, the high voltage produced across the small quantity of liquid in contact with the electrode has a tendency to produce a flash-over inside the controller. This objection is met by providing contactors which introduce a fairly high resistance into the rotor circuit independently of the controller. The relation between forward and reverse torque and resistance in the rotor circuit is an important one and the curves in Fig. 7 show that too high or low a resistance in the rotor circuit results in a reduction of the reverse-current braking effect at full speed, and also show that there is a definite resistance which gives the maximum braking effect at each speed. Heather * was, I believe, the first to point out this fact. He also introduced a special ammeter having a central zero and two elements showing both the magnitude and direction of the stator current and rotor torque in an a.c. winding motor. The present author obtains similar results with a single-phase central-zero indicating wattmeter, the potential supply to which is reversed by contacts on the master controller operating the main contactors. This gives at all times the magnitude and direction of the power supplied to the a.c. motor and is interesting to watch when working regeneratively or with reverse current. The starting and stopping of a.c. induction motors is accomplished by switching " on " and " off " the main current. Reversal of rotation is obtained by interchanging the connections of two of the phases in the case of a three-phase motor, or both phases in the case of a two-phase motor. All this has to be done a great number of times a day, and the switchgear for carrying out these operations has therefore to be of the most robust construction, electrically and mechanically. Both oil-immersed and air-break reversing switches are used. For small sizes oil-immersed direct-operated quick make-and-break switches are satisfactory, but for larger sizes automatic operation is necessary, as the labour of continued reversals is great. Contactor-type air-break switches with powerful magnetic blow-outs are much used and give satisfaction, the wear of contacts being slight. Fig. 8 shows a complete switch of this type. Oil-immersed contacts wear more rapidly, and the oil requires to be frequently renewed. Oil-immersed switches are more compact, and up to 100 amperes on 3 000 volts, if inspected at frequent intervals and the contact faces maintained in good condition, are quite satisfactory. Owing to the considerable mass of the moving contacts and operating mechanism of electrically operated air-break contactors, the force necessary to obtain rapid movement is large and there is a tendency to bounce. Also, the vibration set up by the heavy blows of the closing contacts tends to loosen



FRONT VIEW

FIG. 5.—Diagram of connections of compressor motor.

* *Journal of the South African Institute of Electrical Engineers*, 1912, vol. 10, p. 157.

fastenings and to fracture small interlocks and mechanism. To overcome this trouble, compressed air has been tried as an operating medium, with very satisfactory results. Fig. 9 shows a section of the operating mechanism. An interesting feature observed in these large air-break contactors is that the arc produced when a current of low power factor is broken is much greater than that from a current of high power factor. Apparently the blow-out coils are less effective when current and voltage are considerably out of phase, as in the case of the no-load current of a low-speed a.c. motor.

that power must be cut off at such a point that the inertia of the moving masses is just sufficient to bring the load to bank with the merest touch of the brakes to hold the load as it drops on the keps. Even when winding coal only, the loads vary considerably (some trams are filled by conveyer, and others by hand), or occasional trams of rubbish have to be dealt with, and it will be seen that it requires considerable skill on the part of the enginemen to judge correctly for each differing load the exact point at which to cut off power. The general tendency is to cut off a little too early, with the result that power has to be switched on again to

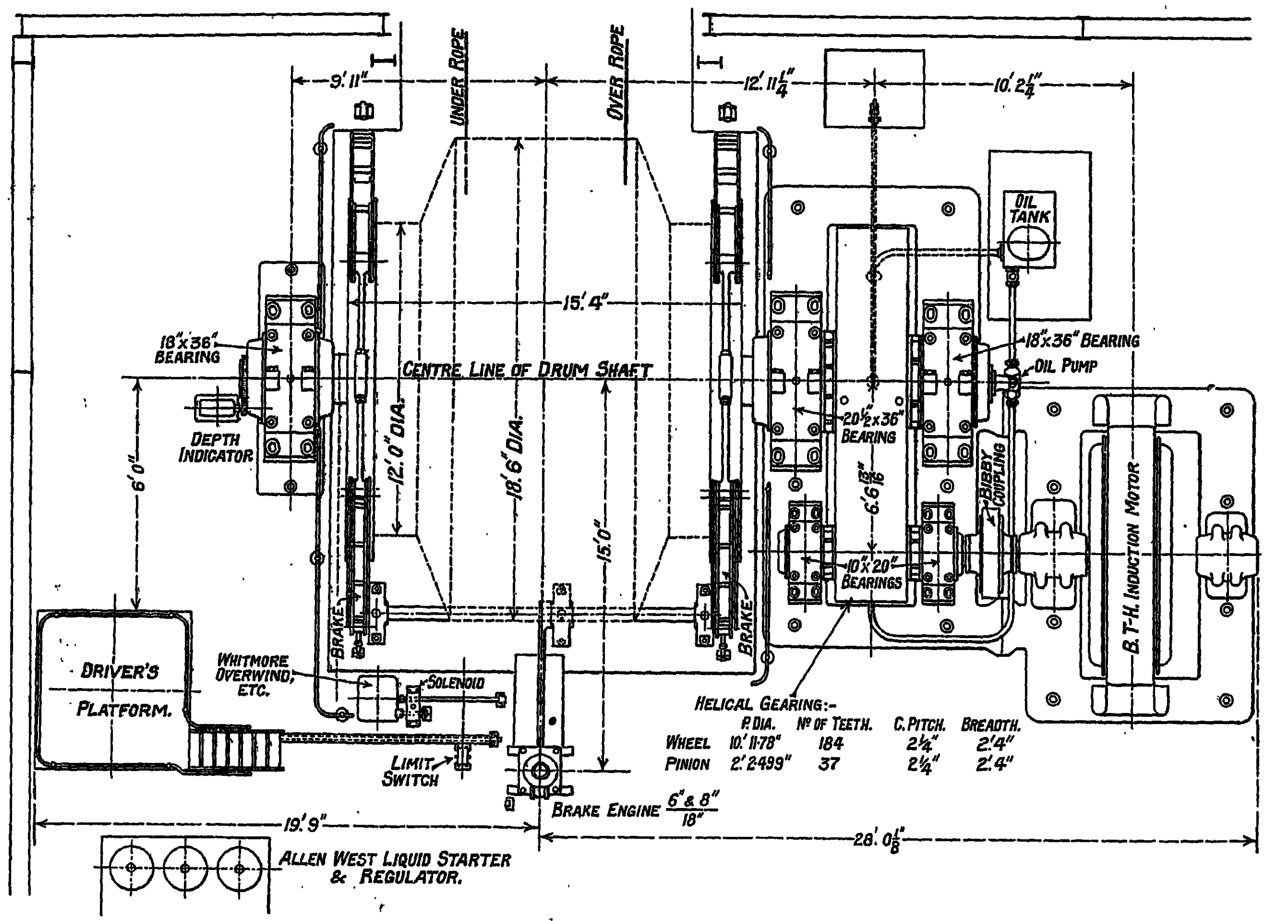


FIG. 6.—Alternating-current electric winder.

In addition to the above consideration in deciding upon the type of winder, the peak-load capacity of the generating station and transmission mains has a great influence. Further, it must be borne in mind that an a.c. winder has a definite maximum speed, which can only be altered by changing the gearing, and its maximum efficiency is only attained at the particular schedule for which it is designed. With all these limitations, however, there is a great field for a.c. winders, from small winders at shallow depths to large winders raising heavy loads at low speeds from greater depths. For maximum efficiency the a.c. winding diagram should be so arranged that no braking is necessary. This means

bring the load to bank. Fig. 10 is a typical wattmeter diagram of such a wind for a cylindrical drum. With a cylindro-conical drum the resulting load on the motor is very heavy, often twice as great as when lifting the normal full cage from the bottom, as the full cage rope is on the large diameter, and the motor receives little help from the empty cage and rope which is on the small diameter. Cutting off too late results in heavy braking.

The advantages of the a.c. system are simplicity, low capital cost, less space occupied, no stand-by losses; and of the Ward-Leonard system, flexibility, ease of control, complete automatic control if desired, lower wear and

tear of brake gear, peak loads on system gradually applied (not instantly as in the case of alternating current) and of shorter duration.

The efficiency varies. For high-speed winds the Ward-Leonard system is usually more efficient; for heavy loads from deep shafts at moderate or low speeds, i.e. where the Stjernberg coefficient is low, alternating current is more efficient. Where it is a question of getting a maximum output from a certain size of shaft with definite limits of weight per wind, the Ward-Leonard system is usually necessary. The two-speed further experience is necessary before mining engineers are prepared to take advantage of the evident improvement possible in the larger sizes.

The d.c. motor is inherently a low-speed machine, and motors of large size to run at speeds down to 30–40 r.p.m. for direct coupling to the drum shaft can be made with high efficiencies. Several large d.c. equipments have recently been installed with geared motors. Fig. 11 shows such a one. Whilst a commercial case has evidently been made out for these, it can only be in first cost. The published efficiency of the geared motors

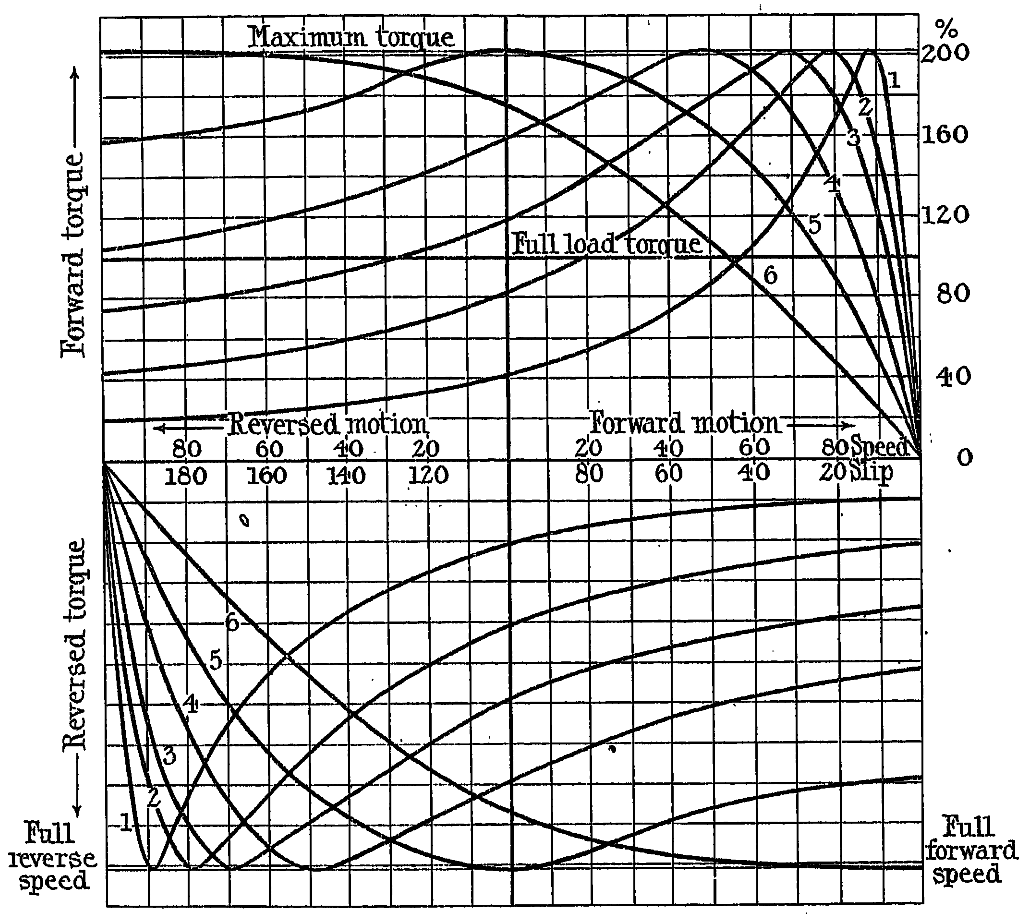


FIG. 7.—Torque/speed curves of 675-h.p., 375-r.p.m. motor.

Curve 1.—Rotor short-circuited.
Curve 2.—External resistance = 1 × (rotor resistance).
Curve 3.—External resistance = 2 × (rotor resistance).
Curve 4.—External resistance = 4 × (rotor resistance).
Curve 5.—External resistance = 8 × (rotor resistance).
Curve 6.—External resistance = 16 × (rotor resistance).

cascade motor shows a considerable increase in efficiency and reduction of peak loads over the single-speed induction motor, owing to the reduced rheostatic losses. In modern designs this type of motor is run up to cascade speed, then the rotor slip-rings are short-circuited (without breaking the stator circuit), and the motor runs up to full speed. Resistance for control is introduced into tappings in the stator circuit. This type of motor has only been tried in moderate sizes and, as reliability is the essential feature of a winding engine, in this case is 94·5 per cent at 350 r.p.m. Corresponding direct-coupled low-speed motors installed by the author have a full-load efficiency of 92·7 per cent. The gearing losses will be at least 2 per cent when new, and higher when the gears begin to wear, so that the balance of efficiency is in favour of the direct-coupled motor. Reliability and maintenance costs are still more in its favour, as there is only one low-speed bearing to maintain, against two low-speed and four high-speed bearings, a pair of gears and a flexible coupling. These

factors will justify a considerably higher first cost in the case of a direct-coupled motor.

An increase in speed of 30 to 40 per cent is permissible on the Ward-Leonard motor by field control alone, and any desired lower speed can be obtained by fixing a stop on the control lever, or better by a resistance inserted in the Ward-Leonard generator field limiting the armature voltage. Thus the winding speed which gives maximum efficiency for any coal output can be fixed and maintained in a Ward-Leonard equipment, the speed being increased from time to time as the mine develops and the output increases.

Until quite recently Ward-Leonard motor-generator sets have been driven by induction motors. Where the generating plant capacity is small compared with the peak loads, flywheels have been introduced to equalize the loads. The losses in these flywheels are appreciable; to run a 12 ft. 6 in. diameter 30-ton wheel and two variable-voltage generators of 1 100 kW at 500 r.p.m. absorbs between 150 and 210 kW continuously. A large part of this loss is in the induction motor which is running at very low efficiency. Further, to enable the flywheel to give up its energy during peak loads, the speed of the set must be reduced. In induction-motor-driven sets this is usually done by inserting resistance in the rotor circuit of the motor by an automatic device. This reduces the rotor efficiency in direct proportion to the increased slip, and the resulting average efficiency of

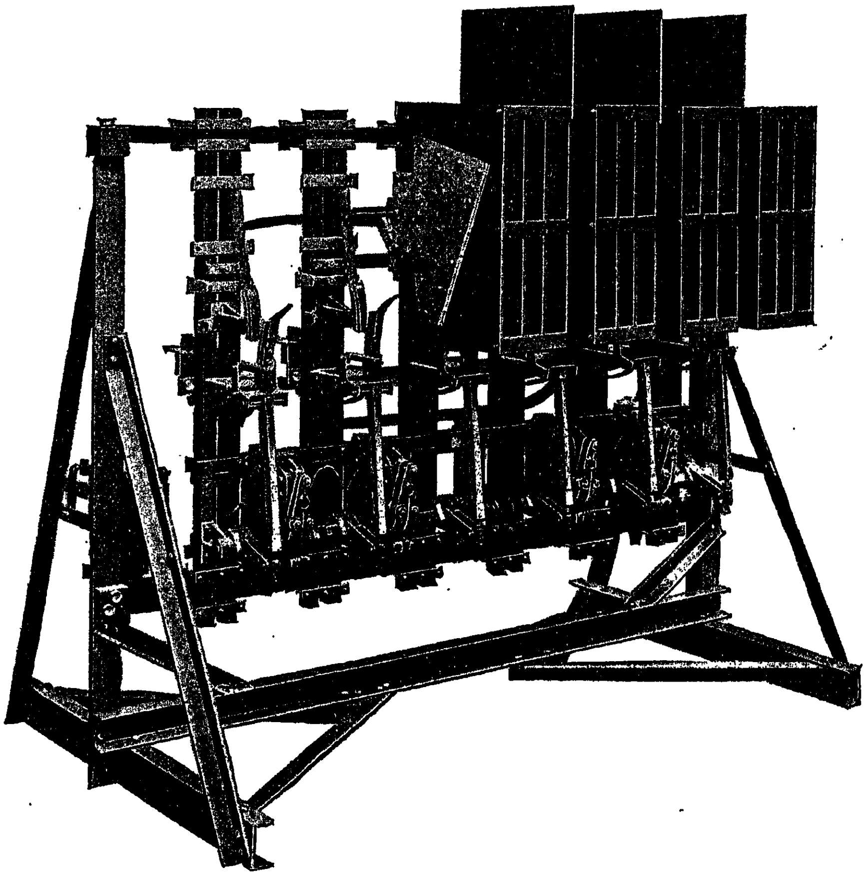


Fig. 8.—Contactor air-break reversing switch.

Table 4.

	Light-load losses	Average efficiency	Peak load	Overall efficiency
	kW	per cent	kVA	per cent
Ward-Leonard generator and synchronous motor ..	80	92·0	3 480	61·0
Ilgner (10 500 V)	205	83·0	3 300	47·0
Ilgner (3 200 V)	150	—	—	—
Ilgner (3 200 V)	115*	—	—	—

* Without flywheel.

the motor over a winding schedule may be as low as 80 or 82 per cent, even in a large machine. If the equipment is run faster than the pre-arranged schedule this may fall to 75 per cent owing to the set being unable to pick up its speed between winds.

Complete equalization for winding schedules raising large tonnage from considerable depths is not feasible, and even partial equalization involves heavy flywheels and correspondingly heavy light-load losses. The author is of the opinion that money can be more suitably spent in increasing the generating plant capacity and in improving the transmission system generally.

If a flywheel with speed variation is not to be used, then the efficiency and reliability of the equipment may be improved by driving the motor-generator set by a synchronous motor. The efficiency of this type of machine will be at least 2 per cent higher than that of an induction motor for similar output. The comparative efficiencies of two equipments of almost equal size, one being of the Ilgner type and the other a plain Ward-Leonard driven by a synchronous motor, are given in Table 4.

The Ward-Leonard set comprises two 1 100-kW 600-volt variable-voltage generators coupled on either side of a 3 250-h.p. 3 200-volt 50-period three-phase synchronous motor designed for 0·8 leading power factor at full load. The main exciter supplying the variable-voltage fields, four motor fields, brake solenoids and other accessories is mounted on an extension of one of the generator shafts and has no outboard bearing. The synchronous motor exciter is mounted in a similar way on the other generator shaft. The whole set runs at 750 r.p.m. This set supplies a winding engine running at 51 r.p.m. and having two 1 400-h.p. motors direct-coupled to a 14 ft. to 22 ft. winding drum arranged for 60 winds per hour, 7·5 tons per wind, giving a normal output of 450 tons per hour from a depth of 650 yards. This can, however, be speeded up to 525 tons per hour if required, without exceeding the B.E.S.A. temperature limits on the various machines.

The Ilgner equipment comprises two 1 035-kW 600-volt variable-voltage generators driven by a 2 000-h.p. induction motor. Two of these sets are supplied at 10 500 volts and the third at 3 200 volts, all three-phase at 50 periods. The flywheels are 12 ft. 6 in. in diameter, weigh 30 tons and are entirely enclosed to reduce windage. The sets run at a full-load speed of 485 r.p.m., and with maximum slip the speed is reduced to 400 r.p.m. The flywheel bearings have forced lubrication and the main bearings on all sets are water-cooled. Excitation is supplied for the Ilgner set by a separate motor-driven exciter of 80 kW with a battery as a stand-by, so that the Ilgner set light-load losses do not include the exciter losses. Each Ilgner set supplies a winding engine having two motors of 1 300 h.p. at 62 r.p.m. direct-coupled to a 14 ft. to 22 ft. winding drum, the output for which they were designed being 60 winds per hour, 6 tons per wind, or 360 tons per hour from a depth of 725 yards.

The overall efficiency is based upon the specified winding schedule. At any lower rate or on an all-day basis the consumptions per ton raised would be still more in favour of the Ward-Leonard set, owing to the lower light-load losses.

The great difference in efficiency is not all due to the relative efficiency of the two systems but is partly due to the winding scheme, the Ilgner set winding lighter loads at higher speeds.

The synchronous motor is of the self-starting and synchronizing type and is started through an auto-transformer with one tapping. The starting current is less than full-load current and the set is run up to speed and synchronized in 60 seconds.

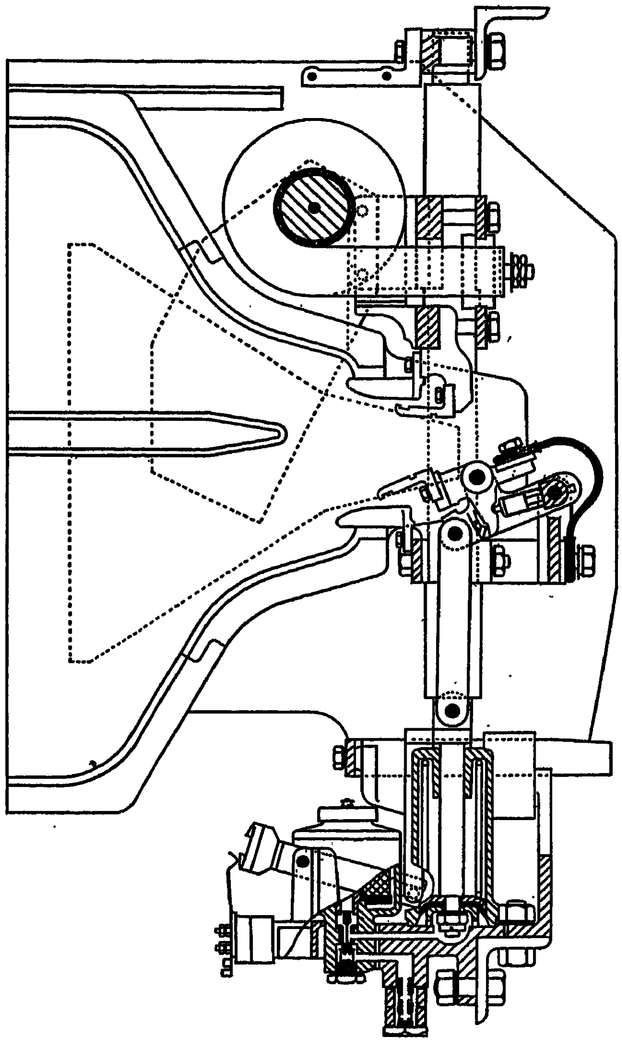


Fig. 9.—Compressed-air-operated contactor.

Advantage has been taken of the improvements in commutation at high speed (resulting from rotary design) to increase the speed of the winder motor-generator sets, and peak loads up to 7 000 h.p. are now dealt with by generators running at 750 r.p.m.

Two valuable and interesting papers on the "Comparison of costs between the Ward-Leonard and Three-Phase Winding Systems" were contributed to the South African Institute of Electrical Engineers, one by Renner in 1911 and another by Ewing in 1916. These refer

to the special conditions existing in South African gold mines, i.e. deep shafts (sometimes inclined) and automatically loaded skips, but the results obtained are easily applicable to our conditions by a few eliminations. For various reasons, balance ropes are not a success in British mines, at least in the author's experience. Of three installations (two alternating-current and one Ward-Leonard) laid out for balance-rope operation, one a.c. equipment ran for only a few months at high efficiency, the balance rope then being damaged beyond repair by a tram falling upon it in the sump. As the gain in efficiency did not represent the cost of a new balance rope every few months, the set now runs without a balance rope. The Ward-Leonard set ran for some years with a balance rope, but the colliery managers, with experience based upon steam winders, or else prejudice, never approved of it and eventually after a similar accident the balance rope was eliminated.

For deep mines and high speeds, cylindro-conical drums are used in preference to balance ropes.

The idea expressed in both the above-mentioned papers—that Ward-Leonard sets must of necessity cost more for maintenance—is incorrect. The maintenance cost of a set of oil-immersed reversing switches on a 1 100-h.p. a.c. winder amounted to £150 per annum; wear and tear on the liquid controller is high owing to the corrosive action of the electrolyte. Slip-ring brushes wear about ⅛ in. in 6 000 hours' operation.

The maintenance of a high-speed motor-generator set consists chiefly of brush renewals. The average wear in 6 000 hours' running of a 750-r.p.m. 1 100-kW set is $\frac{1}{16}$ in. per brush. Slip-ring brushes wear more rapidly, ⅜ in. being the average in 6 000 hours. The wear of the low-speed d.c. winder motor brushes is less than $\frac{1}{32}$ in. in 6 000 hours. In one large set under the author's observation the main motor brushes have not been changed in 11 years and the wear is less than ¼ in. The motor-generator set has also a number of the original brushes still running. The average cost per annum for brush renewals, including labour for bedding, will not exceed £50 for a 1 400-h.p. Ward-Leonard set and winder motor. Bearings appear to run indefinitely on high-speed motor-generator sets. They are mostly flood-lubricated and water-cooled.

The 1 100-h.p. a.c. equipment referred to is gear-driven and, although no figures are yet available for the life of these low-speed gears, an estimate of 20 years appears reasonable.

The average yearly maintenance cost would be as follows:—

An 1 100-h.p. a.c. winder with oil-immersed switches	£250
An 1 100-h.p. a.c. winder with air-break contactors	£150
A similar Ward-Leonard set..	£105

The efficiencies of Ward-Leonard sets have improved since these papers were written; otherwise their findings hold to-day. Briefly these are that a.c. winders will effectively carry out all the operations they may be called upon to do, but that from 50 per cent of their schedule load upwards the Ward-Leonard winder is more efficient in straightforward weight-raising, and for all weight-lowering and low-speed work Ward-Leonard operation is considerably more efficient. In addition the control is safer, smoother and simpler and lends itself to complete automatic operation.

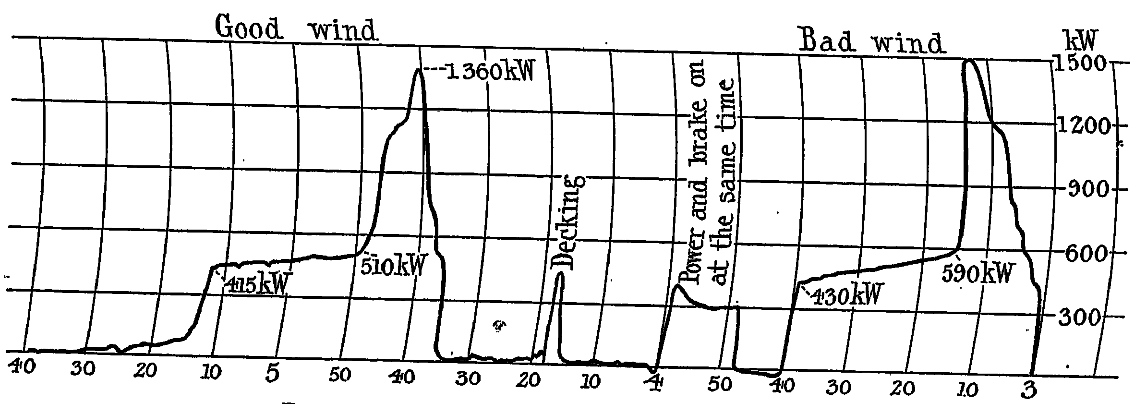


FIG. 10.—Alternating-current winder wattmeter chart.

In the author's experience, winding-engine men taken directly from steam winders require at least 50 hours' practice in a.c. winder control before they can be relied upon, and many months' experience before they can work to a schedule so as to achieve full efficiency. Men taken direct from a steam winder will drive a Ward-Leonard winder with full confidence in an hour or two, and will obtain full efficiency on a schedule in a couple of weeks. The difficult operation of extracting water with a water barrel during sinking operations is mastered in a few attempts on a Ward-Leonard set, but takes twice as long on an a.c. winder, even with a highly skilled driver.

The a.c. winder has a finite maximum output, while the Ward-Leonard set can be speeded up, if required, to the limit of the heat capacity of all the machines. Prices have varied so rapidly in the last few years that a comparison of capital costs is difficult. An approximation based upon a number of recent installations is that the complete Ward-Leonard set, including drum, etc., costs 30 per cent more than an a.c. set for an output of 250 tons per hour from a depth of 600 yards. In all the recent winder equipments for which the author has

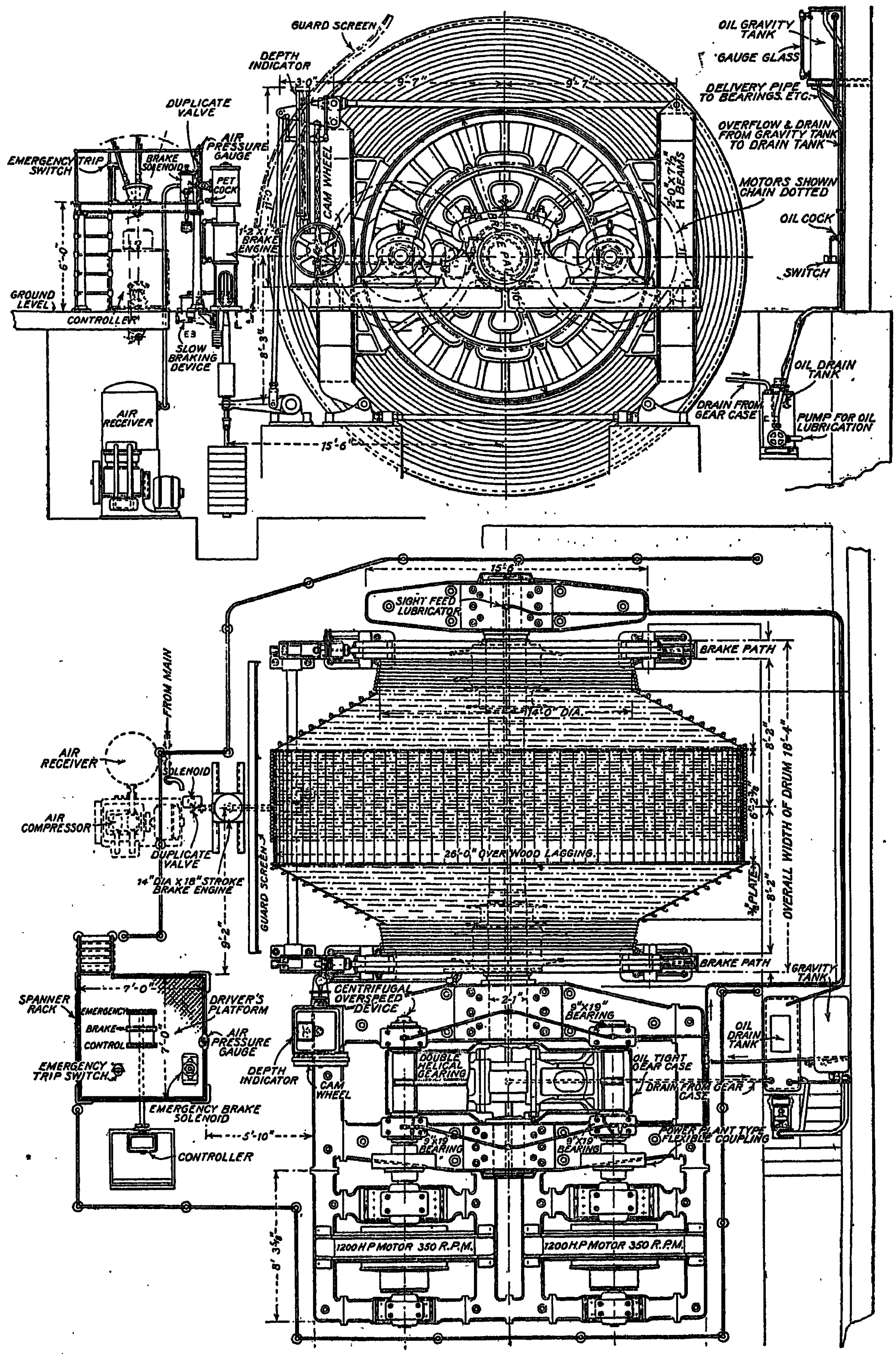


FIG. 11.—General arrangement of the Harworth geared winder.

been responsible, duplicate generators have been provided on the motor-generator sets, each giving half the final voltage. During the sinking and development of the mine, one motor-generator set can thus run two winders at half speed with lower light-load losses and capital costs. Later, when the full output is required, the two generators are connected in series and full speed is obtained on the winder motors, which may also be duplicated if desired. During normal working the winders are run at full speed only during the working shift, and at half speed during the afternoon and evening shifts. These changes are simply and quickly made on a plug board having horizontal and vertical busbars.

An alternative scheme to the usual steam winder and mixed-pressure turbine for isolated collieries has recently been developed, and an equipment is now installed for an output of 3 000 tons per day from a depth of 1 000 yards. The general arrangement is shown in Fig. 11. A Ward-Leonard motor-generator set is driven through gearing by a high-speed turbine. This supplies the two winding motors, the motors being controlled by varying the voltage of the Ward-Leonard generators. A flywheel is provided which takes the peak loads, the turbine governor gear permitting a large range of speed, so that a moderate size flywheel can supply a considerable amount of energy. A valuable feature of this scheme is that full advantage can be taken of the flywheel energy, as speed reduction is not accompanied by a corresponding reduction in efficiency. This plant has been in satisfactory operation for some months and further similar equipments are in progress.

Part 3.

The ratio of winding, compressing and ventilating loads (which may be steam-driven) to pumping, haulage, surface loads and lighting (which are usually electrical) is an important factor in fixing the type of power plant. If the available low-pressure steam from the first three is just sufficient to produce the necessary electricity for supplying the remainder, then it would appear economically sound to install steam winders, fan engines and compressors and mixed-pressure turbines for supplying the remaining power. As, however, the high-pressure steam consumption of mixed-pressure turbines is higher than that of "straight" high-pressure machines, and also as electric winders are twice as efficient as steam winders, and large boiler plants are more efficient than small boiler plants, there are very few cases where a mixed-pressure steam-winder plant can compare favourably with an all-electric plant.

Steam-winder manufacturers usually give consumptions per shaft horse-power or per hour for a given schedule, and ignore stand-by losses. The low-pressure steam from the winders is referred to as a sort of gratuity given to users of steam winders. The heavy high-pressure steam consumption of mixed-pressure turbines is assumed to be useful in maintaining a steady load on the boilers. Figures will be given later in the paper to show that stand-by losses are considerable and, in addition to the smaller boiler plants being less efficient under the varying load, a better class of fuel has to be used than in the large stations.

In conclusion, a few examples are given of actual collieries, (1) steam-operated, (2) electrically operated, and (3) during the transition stage.

The first colliery considered has two winding engines, each operating tandem deck cages raising an average of 50 cwts. per wind, the depth of the shafts being 520 and 450 yards. The engines are of modern type with Corliss valves and governor-controlled cut-off gear. Their consumption per wind calculated from indicator cards is

No. 1 winder .. 175 lb., or 43·8 lb., per shaft h.p.
No. 2 winder .. 166 lb., or 48·2 lb., per shaft h.p.

The pressure is 120 lb./sq. in. and the superheat 425 deg. F.

The fan engine was a rather old vertical type of about 600 h.p. with rope drive.

The three compressors were of the low-speed horizontal Corliss-valve type; two ran during the working shift and one during the remainder of the day. The measured steam consumption of these engines was 28–32 lb. per b.h.p.-hour. All the engines exhausted into a gas-holder type of receiver, and a 2 000-kW mixed-pressure turbo-alternator of modern type utilized the low-pressure steam and generated an average of 86 000 units per week. This set ran only during the working shift.

Average water evaporated by the boilers (three 30 000-lb. Babcock with chain-grate stokers and economizers, and four Lancashire boilers) per week	9 640 000 lb.
Maximum hourly output during the working shift	120 000 lb.
Maximum hourly output during the off shift	60 000 lb.
Average coal consumption per week ..	589 tons
Coal raised per week	12 500 tons
Percentage coal consumption	4·72

11 000 additional units were supplied.

When an electrically-driven fan was installed and the fan engine shut down :—

Water evaporated (average) per week ..	9 124 800 lb.
Coal consumption per week	541 tons
Reduction per week	48 tons
Units consumed by the fan (average) per week	57 000

The compressors, which previously were short of steam, were now enabled to run up to their full capacity, giving a considerably greater output of air.

The compressors were next shut down and the air supplied from the central generating station at the rate of 40 000 000 cubic ft. per week.

Water evaporated per week	4 940 000 lb.
Coal consumption per week	310 tons

TABLE 5.

	Units per week	Units per ton
Present Conditions.		
	kWh	kWh
Winders and mixed-pressure turbines	86 000	6·88
Fan consumption	57 000	4·55
Compressed air	151 700	12·10
Units in addition to those generated by mixed-pressure turbine supplied for colliery washery, etc.	11 150	0·89
Total	305 850	24·42
Estimated Consumption if Winders be Electrified.		
Winders	52 500	4·2
Fan as above	57 000	4·55
Compressed air	151 700	12·10
Colliery washery, etc.	90 000	7·20
Total	351 200	28·05
Comparison with All-Steam Colliery.		
Total coal consumption for winders, compressors, fan engines and mixed-pressure turbine	4·72 per cent of output	
Additional units used over those produced by mixed-pressure turbine	11 150	0·89
Extra compressed air	64 700	5·17
Total	75 850	6·06

The air consumption increased from 8 000 to 9 000 cubic ft. per min. to 15 000 to 16 000 cubic ft. per min. during the working shift, or an average of 70 000 000 cubic ft. per week, the pressure also being increased from 60 lb./sq. in. to 65 lb./sq. in.

The steam winders and mixed-pressure turbines were now the only loads on the boilers, and the Lancashire boilers were shut down, the load being taken on the three water-tube boilers. The light-load losses and auxiliary consumption of these boilers amounted to 10 000–12 000 lb. per hour. Taking the average consumption per wind as 175 lb. for No. 1 winder and 166 lb. for No. 2 winder, over a complete 24 hours the results were as follows:—

Total net consumption for 720 winds of No. 1 winder and 635 winds of No. 2 winder	232 000 lb.
Total light-load losses, feed pumps and auxiliaries for 24 hours	254 000 lb.
Gross consumption, per day, should be ..	486 000 lb.
Actual evaporation, per day	760 000 lb.
Difference, per day	274 000 lb.
High-pressure steam to the mixed-pressure turbine accounted for, per day	224 000 lb.
Left for blow-downs, blowing-off and other unaccounted losses, per day	50 000 lb.

The medium-pressure turbine runs only during the working shift from 7 a.m. to 2 p.m., and the average number of units generated in 7 hours is 14 300, or 2 050 per hour.

The actual high- and low-pressure consumption of steam for winding and generating these units is 58 000 lb. per hour, or an average of 28·3 lb. per unit.

Usually in getting out comparative calculations of steam and electric winding plants the net steam required for winding is taken and then an addition of 12 to 15 per cent made for light-load losses, occasional winds during afternoon and night shifts, and boiler auxiliaries. Actually the average steam consumption during the 7 hours' working shift at this colliery is 480 000 lb., the consumption during the afternoon and night shifts being 280 000 lb. (760 000–480 000), or 58 per cent of that during the working shift. A certain amount of coal-winding is carried out during the afternoon shift from 2.30 p.m. to 4.30 p.m., but when this is not done the evaporation is only slightly reduced. Similar figures for afternoon and night evaporations are obtained from other collieries.

If the steam winders were replaced by electric winders, as they have been at other similar pits, the number of

TABLE 6.

*Comparison of Steam with Electric Winders.**

Winder	Number of winds: Coal	Rubbish	Men	Material	Total	Tons raised: Coal	Rubbish	Consumption per ton of coal raised: Coal	Units	Per cent of output
								lb.	kWh	
Steam	1 572	232	717	244	2 765	6 839	1 200	33·2	—	1·48
Electric	1 650	240	848	250	2 988	7 148	1 240	—	3·7	—

* The figures relate to one complete week's working in each case.

units consumed would be 2·46 per ton of coal raised, or, for men, material, rubbish and coal, 4·20 per ton of coal raised. At 12 500 tons per week this is equal to 52 500 units. The results are summarized in Table 5.

Tables 6 and 7 give actual values for a smaller colliery raising 1 000 to 1 250 tons per day, showing the effect of replacing the steam winder by an electric winder. The fan and compressed-air systems had been converted before accurate water evaporation records were available, but the coal consumption before the conversion was $5\frac{1}{2}$ per cent of the coal raised, with a much lower consumption of compressed air.

Table 7 summarizes all the loads at this colliery.

TABLE 7.

	Units per week	Units per ton
	kWh	kWh
No. 1 electric winder	26 400	3·7
No. 3 electric winder	1 500	0·21
Fan	28 560	4·00
Compressed air	108 200	15·1
Other colliery uses	26 540	3·71
Total	191 200	26·72

Table 8 shows another gradual conversion. The compressor in this instance was shut down first, the fan afterwards and the winding engines finally. There was no mixed-pressure turbine at this colliery and no water-measuring apparatus. Comparative coal consumptions only can be given. Compressed-air consumptions have in all cases increased since the conversions, due partly to the inadequacy of the steam-driven compressed-air plant and partly to the increased use of conveyers and other air engines.

These results show that wherever accurate records are available, electrification of the whole of the machinery at a colliery can be proved to be a sound commercial proposition. The reduction in pit-head costs resulting from a highly efficient plant is appreciable, although the total cost of power is small compared with the labour costs at a colliery, and the usual method of costing makes it difficult to prove the reductions.

The principal effect of electrification is to reduce the amount of unskilled labour employed at the pit-head, this unsatisfactory and difficult-to-manage gang being replaced by a few skilled hands.

Electrical plant has one special advantage over other types in that the actual consumption of every machine or group of machines can be continuously recorded and any waste checked. Further, electrical plant retains its high efficiency without the constant adjustments and renewals necessary in other machines.

TABLE 8.

	Units per week	Units per ton	Percentage of coal raised used for power
Steam Winding, Fan and Compressor Engines.			
	kWh	kWh	per cent
Coal consumption for one fan engine, one winding engine and one compressor	—	—	6·5
Electrical units consumed for pumping, haulage and general pit use	16 300	3·5	—
Steam Compressor Shut Down.			
Coal consumption for one winding engine and one fan engine	—	—	5·08
Compressed air supplied from central station	43 000	9·25	—
Colliery electrical units as before	16 300	3·5	—
Total	59 300	12·75	
Fan Engine Shut Down.			
Coal consumption with one winding engine only	—	—	2·4
Compressed air as before	43 000	9·25	—
Colliery units, including No. 2 winder electrified	28 000	6·00	—
Fan units	40 300	8·66	—
Total	111 300	23·91	
Colliery Completely Electrified.			
Units consumed by Nos. 1 and 2 winders	40 600	7·13	—
Compressed-air units ..	195 000	34·3	—
Colliery units, including washery	40 260	7·08	—
Fan units	50 400	8·85	—
Total	326 260	57·36	
Comparison with Original Steam-driven Plant with Increased Loads Supplied from Central Station.			
Steam plant	—	—	6·5
Extra compressed air ..	152 000	26·65	—
Extra units for colliery and washery	24 000	4·22	—
Total	176 000	30·87	

DISCUSSION BEFORE THE INSTITUTION, 19 FEBRUARY, 1925.

Mr. C. P. Sparks: The author refers at the conclusion of the paper to the advantage of being able to obtain exact records. The ease of making exact measurements with an electric drive has done more to enable us to make rapid progress in conversion than any other factor. The main obstacle to progress is the difficulty of comparison with operation under the older conditions. The main reason for electrification is the saving in labour, maintenance and fuel, and the ease of meeting additional power requirements when once an adequate electric supply is available. The author rightly emphasizes the importance of eliminating stand-by losses through the use of electricity, and the results given in the paper confirm the general experience that the saving of fuel by conversion to electric drive amounts to between one-third and two-thirds of the fuel used under the older methods. Dealing with the use of synchronous motors, in view of the importance of maintaining pressure of supply with a heavy fluctuating load on individual feeders, and of keeping down the cost of distribution, the full particulars given by the author of synchronous motors and their methods of control are most valuable. The difficulties of operating with a low power factor were fully appreciated at least 10 years ago. At that time the large system of the Powell Duffryn Steam Coal Co. in South Wales was operating with an output of some 50 million units per annum. The power factor of the stations at that time ranged between 0·7 and 0·8. In view of the progressive fall in power factor with increasing load, the late Mr. George Hann and myself decided that the earliest opportunity must be taken to improve the power factor of this system. The result of the use of synchronous motors on a large scale, driving air compressors, fans and winders through motor-generators, has been to raise the station power factor to between 0·8 and 0·9 with three times the output, now at the rate of some 150 million units per annum. The power factor has been raised and the general pressure on the system much improved, although the system is now operated, owing to its growth, with transformers having higher reactance than when operating on a smaller scale. The author refers to the efforts made to improve the efficiency in winning coal by the use of electricity, but while much has been done much remains to be done. Table 2 shows the average consumption for a typical South Wales colliery, of 32 units per ton of coal raised. The units required per ton vary widely; in some parts of the world the natural conditions are such that coal can be won for the expenditure of a much smaller amount of energy. During a recent visit to the United States I inspected some large colliery undertakings which were operating under favourable natural conditions, and although the whole of the power requirements were supplied electrically the units per ton of coal raised varied from 3 to 5. It would be difficult for us in South Wales to compete with such figures were it not for the fact that these mines are distant from the sea and therefore the question of transport has a material bearing. Of the total of 32 units in Table 2, twenty are used for compressed air, and while I am in agreement with the author as to the efficiency of compressed-air transmission being high, I think that this statement is really misleading, because what has to be taken into account is not only the transmission of the compressed air, but its use; and the compressed-air engine is very inefficient. In my opinion it is most important to improve electrical apparatus and its control so that the use of compressed air can be largely dispensed with. Another thing that is very necessary is better lighting at the face, as this will reduce the risk of accident and at the same time greatly reduce the cost by improving the efficiency of labour. The introduction of the miners' electric lamp with metal-filament lamp has enabled the standard of lighting to be at least doubled in the last 12 years, but there is room for material improvement. In comparing colliery with other power stations, although, of course, every power station should be reliable, reliability is absolutely essential in the case of collieries. One has only to consider the winder, ventilating fans and the pumps to appreciate this point. The author refers to the use of low-grade fuel. In the old days any refuse was used in colliery boilers, but with the improvement of low-grade fuels by washing, and the higher costs of labour to-day, it does not pay to try to burn what I might call dirty fuel, and there is no doubt that the modern tendency, even in the smaller collieries, is to use a higher grade of fuel. The author refers to the advantages which pulverized fuel possesses, but it is doubtful whether the low-grade fuels in their raw form will prove to be suitable for pulverizing. The author refers to the question of reversing switches. These have a heavier duty than any other type, as they have to operate every 45 to 60 seconds. Within the past 2 or 3 years it has been definitely found that, although making these switches larger increases the factor of safety, and although by frequent inspection and changes of oil the risk can be minimized, an oil-immersed switch is not suitable for this work. The best solution is to use a type of air-break switch, as mentioned in the paper. The author draws attention to a point of more than ordinary interest in regard to switches. On page 528 he says: "Apparently the blow-out coils are less effective when current and voltage are considerably out of phase, as in the case of the no-load current of a low-speed a.c. motor." He draws attention here to a matter of great interest to switchgear makers and to users of switchgear generally. The failure of switchgear, which has a large factor of safety when tested under normal conditions, is no doubt due to the greater "arc energy" under the conditions cited. In regard to winders, I entirely agree with the author that the synchronous motor-generator is the right line of approach, especially where the winders are large, as the Ward-Leonard system gives perfect control and is almost essential for the adjustments required during sinking.

Mr. J. A. B. Horsley: The author discusses financial considerations that affect the choice as between steam and electric winders, and describes the technical differences which influence the choice of d.c. or a.c. drive;

but with the exception of a passing reference to the possibility of complete automatic control with the Ward-Leonard system, he makes no reference to the subject of automatic control of the speed during the wind. I submit that such automatic control is of real value and cannot be put aside as a refinement which need not be considered. Methods of automatically controlling the speed are possible with a.c. winders as well as with d.c. winders. I am not referring, of course, to the overwind preventer—that is a statutory requirement—but to some device to control the speed of winding at different stages in the shaft so as to prevent the winding-engine man from increasing his speed beyond that which is safe both in mid-shaft and at either end. During the course of inspection in the Midlands not long ago I saw a recently-installed three-phase winding equipment with which such a device had been incorporated. This was so arranged that if certain predetermined speeds were exceeded the power was cut off and the brakes were applied. I suggested to the engineers responsible that they should devise some means of testing the over-speed preventer by "faking" the controlling rheostat in such a way as to simulate an emergency when running at, say, one-quarter full speed. My suggestion was accepted, both by the users and the manufacturers, and a very simple method has been evolved whereby a spring-return switch is included in the rheostat circuit; when this switch is depressed a certain section of the resistance is cut out so as to enable the automatic device to function at quarter speed as if the engine were really running at full speed.

Mr. J. H. Johnson: I should like to associate myself with Mr. Sparks's remark that the author should not pay too much attention to the relative efficiency of transmission by air and electricity over small areas, but that the question of efficiency throughout the whole system should be considered. It has long been understood and appreciated that over short distances the efficiency of air is higher than that of electricity; but one has to take the whole of the plant as used when making a direct comparison. The author refers on page 523 to the use of the salient-pole synchronous motor. This type of machine has not been largely employed in this country and on the Continent, owing to the fact that it has a somewhat low starting torque and demands a heavy starting current. The auto-synchronous motor or induction synchronous motor has been applied to practically every type of industrial machine at present in use—both in mining and in other industries. The author is rather generous to the salient-pole machine when he refers to an efficiency of 96·7 per cent, compared with the 93·2 per cent for the ordinary induction synchronous motor. If the matter is looked into it will be found that, under ordinary conditions, the efficiency of the former is only about ½ to 1 per cent higher than that of the latter, due mainly to the use of a higher-voltage excitation current. Otherwise the overall dimensions and efficiency remain the same, and the advantages of the cylindrical type are (1) high starting torque at 2 to 3 times full-load torque, (2) automatic synchronizing against full-load torque, and (3) a starting current under ordinary conditions not exceeding the full-load current. The author refers on page 525 to the friction losses incurred in the flywheel of the Ilgner sets. Those can be largely reduced by highly polishing the flywheel and enclosing it in a partial vacuum. The cost of the auxiliary gear is compensated for by the reduced friction losses.

Mr. T. J. Sack: The paper is entitled "Electricity in Mines," but I think that a more suitable title would have been "Electric Power in Mines," as one of the most important uses of electricity in mines is for lighting, and that apparently has been quite ignored. I had hoped to find that some further progress had been made in the lighting of the coal face on the lines laid down by Prof. Thornton in a paper * read before this Institution, in which he suggested that a high frequency of, say, 165 periods, and a low pressure, approximately 25 volts, should be used. It is ridiculous that all this money should be spent on hauling coal and getting it up to the surface, and scarcely any on the actual coal-getter, as far as providing him with better light is concerned. At the present time he works with, in some cases, as low as 0·008 foot-candle on his work. Coal-owners pay £500 000 per annum as compensation for miners' nystagmus, which has been proved to be entirely due to inadequate illumination.† There are a great many limitations to the present design of miners' electric hand-lamp. One of the chief of these is the weight: it has to be limited to 5 or 6 lb. Another factor is the rough usage which these lamps have to withstand. A 2-volt accumulator is the one best fitted to fulfil the foregoing conditions, but 2 volts happens to be the very worst voltage from the bulb-makers' point of view. Owing to physical laws, it is impossible at present to make a really efficient 2-volt bulb that will have a life long enough to satisfy the colliery owners.

Mr. W. C. Mountain (*communicated*): The author has divided his paper under various headings which I propose to deal with in order, and I hope I may be forgiven for introducing into my remarks a good deal of the commercial side of the subject, as I feel, and always have felt, that the introduction of electricity into any enterprise is dependent entirely upon its value commercially. We all know that there are very great opportunities for the use of electricity, particularly in colliery work, but it must not be taken for granted that electricity can be introduced into all sections of colliery work, unless it can be generated or supplied at a price per unit which will render its use economical in comparison with steam, and there are a number of points in the paper with which I propose to deal on these lines.

Boilers.—From my own experience, which has now extended over nearly 43 years (during which time I have been principally engaged upon the development of electrical work in collieries), I have found that probably the most inefficient section is the boiler plant. One finds Lancashire boilers installed in many collieries in considerable numbers and of all ages and sizes, and it is no uncommon thing to find a battery of boilers with a certain number of new boilers having a working pressure of 150 lb. per sq. in., and amongst the battery are several old boilers with a working pressure of probably only 70–80 lb. per sq. in., yet these are retained in use and this

* *Journal I.E.E.*, 1924, vol. 62, p. 481.

† Report No. 65 of The Miners' Nystagmus Committee of the Medical Research Council.

means that the working pressure of the battery is limited to the highest pressure for which the old boilers are suitable. In addition to this, the boilers are generally improperly housed, the boiler flues are in a bad condition, and in very many cases superheaters and economizers are omitted altogether.

Lancashire boilers have necessarily (due to their design) a very limited grate area and consequently, if it is desired to get the utmost steaming capacity out of the boilers, a good coal must be used, otherwise inferior coal will necessitate the use of special fire grates with steam jets, etc., to force the boilers as much as possible. It seems to me that for some reason (which it is difficult to understand) many colliery engineers are prejudiced against the use of water-tube boilers, but they are coming more and more to the front and there is no doubt that if it is desired to burn unsaleable and inferior fuel, it can only be done satisfactorily and economically in water-tube boilers with either induced draught or balanced draught.

The author deals with the use of coke-oven gas to be utilized either in gas engines or under boilers, and this is a subject to which I have given a considerable amount of attention, particularly in connection with a large scheme in the Midlands. It is frequently assumed that the thermal efficiency of gas engines is two or three times as high as that of steam turbines. This, however, is a mistake, and a very exhaustive consideration of the whole subject led me to conclude that the ratio of power which could be obtained with high-pressure steam turbines with gas-fired boilers, to that with gas engines using coke-oven gas, was 10 : 14; in other words, with steam turbines 700 kW and with gas engines 1 000 kW could be obtained with the same consumption of gas. The calorific value of the gas was 400–450 B.Th.U. per cub. ft. and it was assumed that it required 3·75 cub. ft. of gas to evaporate 1 lb. of water at 212° F. into steam at 160 lb. per sq. in. pressure and 150 deg. F. superheat. In connection with this report I prepared some tables which are shown here as Tables A, B, C and D.

These tables are so arranged that the figures can be easily adjusted to suit varying conditions, and the conclusion to which they led me was that it would be far better to adopt water-tube boilers (gas-fired) and steam turbines, in preference to gas engines, as I felt that turbines were much simpler, would require less attention in running and, although the thermal efficiency was not so high as with gas engines, the commercial efficiency, i.e. the cost of current produced, was greater. It would be of interest if the author would give some information on this point, as I think that his company have installed gas engines, also high-pressure and mixed-pressure steam turbines.

As an example of what can be done with boiler plant, I recently inspected a modern installation of Babcock and Wilcox boilers, consisting of four boilers each of 30 000 lb. capacity per hour, and 150 lb. per sq. in. working pressure. They were burning (on chain-grate stokers) refuse coal and dirt which had been lying on the pit-heap for years, together with 25 per cent of small coal of an inferior quality. The result was a saving exceeding £2 000 per month in the cost of steaming, and it was expected that the whole cost of the boilers would be saved in from 1½ to 2 years. The original boiler plant consisted of 18 Lancashire boilers, each 30 ft. long by about 8 ft. diameter. The saving in stokers' wages alone by introducing water-tube boilers with chain-grate stokers, and a proper means of distributing the coal to the boilers, exceeded £50 per week.

Fan driving.—The author refers to the question of driving colliery fans by synchronous motors. I entirely agree with this provided that the fans themselves are driven by ropes or belt, and I think that this method of driving has very considerable advantages as it enables the speed of the fan to be varied by changing the pulleys at very small cost. It is particularly useful where collieries are being developed, and it is only necessary to run the fan at a low speed in the early days. I have used cascade motors designed for two-thirds and full speed. This is a useful arrangement, so much so that in one colliery we found that, although the colliery company estimated that they required the full capacity of the fan at full speed, we ultimately found that at two-thirds of full speed we were able to give them the ventilation they required, i.e. with about half the original water gauge estimated as necessary and two-thirds of the volume of air. I have also used for fan drives ordinary slip-ring induction motors with phase advancers, with very satisfactory results. It is, however, very important, where it is proposed to drive fans electrically, to consider what the cost will be for current, and in connection with a drive of this description—for which a supply had been taken originally from a supply undertaking—the following comparative results between electric drive and steam drive were obtained :—

Capacity of fan, cub. ft. per min. ..	350 000
Water gauge, inches	5
Air horse-power $\left(\frac{350\,000 \times 5 \times 5{\cdot}2}{33\,000}\right)$, say ..	300
Brake h.p. of fan at 70 per cent eff.	425
Units per hour (425 b.h.p. × 830 watts per h.p.)	350
Units per annum (350 × 8 760)	3 066 000
3 066 000 units at 0·5d. per unit ..	£6 387 per annum
3 066 000 units at 0·33d. per unit ..	£4 216 per annum
3 066 000 units at 0·25d. per unit ..	£3 194 per annum

I investigated this to see what the probable cost would be if the fan were steam-driven, with the following result :—

Fan requires, say, h.p.	425
Steam per b.h.p. per hour, lb.	20
Total steam per hour, lb.	8 500
Evaporation per lb. of coal, lb.	7
Total coal per hour, lb.	1 214
Hours running per annum	8 760
Tons of coal per annum $\left(\frac{1\,214 \text{ lb.} \times 8\,760}{2\,240}\right)$, say	4 800
Boiler coal per ton, say	10s.

Approximate cost of a compound high-speed steam

TABLE A.

Cost of Current produced by One 1 000-b.h.p. Gas Engine, and 700-kW Generator with Coke-Oven Gases of a Calorific Value of 400–450 B.Th.U. per cubic foot.

Cost of generating plant with gas-cleaning plant for 700 kW	Load factor	Units produced per annum	Gas per kWh (400–450 B.Th.U.)	Cost of gas per annum, at 6d. per 1 000 cub. ft.	Cost of labour for gas engines, cleaning, plant repairs, oil and stores, and insurance per annum	Cost per unit on capital at 12½ per cent for interest and depreciation (£30 000)	Cost per unit of gas consumed at 6d. per 1 000 cub. ft.	Cost per unit for labour (£2 500)	Total cost per unit generated
One 1 000-b.h.p. engine; one 700-kW alternator; 1 switchboard; 1 suitable power house; 1 crane; 1 gas-cleaning plant; 1 gas holder; 1 starting plant; gas pipes; water pipes and pumps. Total, £30 000.	per cent 100	6 000 000	cub. ft. 40	£ 6 000	3 engineers, 3 labourers, 1 fitter, 1 labourer, etc. £2 500.	d. 0·15	d. 0·24	d. 0·1	d. 0·49
	90	5 400 000	42	5 560		0·166	0·25	0·11	0·526
	80	4 800 000	44	5 250		0·188	0·26	0·125	0·573
	70	4 200 000	46	4 750		0·20	0·27	0·143	0·613
	60	3 600 000	48	4 300		0·25	0·285	0·166	0·701
	50	3 000 000	50	3 750		0·3	0·3	0·2	0·8
	40	2 400 000	52	3 100		0·375	0·31	0·25	0·935
	30	1 800 000	54	2 450		0·5	0·325	0·33	1·155
	25	1 500 000	55	2 050		0·6	0·33	0·4	1·33
	20	1 200 000	56	1 650		0·7	0·335	0·5	1·535

Note: If duplicate plant is installed the increased cost per unit can be ascertained by adding to the unit price for one plant the interest and depreciation on the additional plant.

TABLE B.

Cost of Current produced by One 1 000-kW Turbo-Generator with Two Lancashire or Water-Tube Boilers. Steam Pressure 160 lb. per sq. in. (gauge); Superheat 150 deg. F.; Vacuum 27·5 in.; Coal 12s. per ton.

Cost of generating and boiler plant (1 000 kW)	Load factor	Units produced per annum	Coal per kWh	Coal used per annum	Cost of coal per annum at 12s. per ton	Cost of labour for engineers and stokers per annum, including water and boiler cleaning	Cost per unit on capital at 12½ per cent for interest and depreciation (£2 625)	Cost per unit for coal consumed	Cost per unit for labour (£1 552)	Total cost per unit
One 1 000-kW mixed or high-pressure turbo-generator; condensing plant; power house with crane; main switchboard and coupling cables; steam pipes; cooling plant, etc., £16 000. Two 30 ft. by 9 ft. 3 in. Lancashire boilers with seatings and chimney, £5 000. Total, £21 000.	per cent 100	8 800 000	lb. 3	tons 11 600	£ 6 960	3 engineers and 3 stokers, one each shift, one ashman 1 shift, £26 per week, £1 352 per annum. Boiler cleaning and sundries, £200. Total, £1 552 per annum.	d. 0·0715	d. 0·19	d. 0·042	d. 0·3035
	90	8 000 000	3·2	11 200	6 720		0·079	0·2	0·045	0·324
	80	7 000 000	3·4	10 600	6 360		0·09	0·218	0·053	0·361
	70	6 200 000	3·6	10 200	6 120		0·102	0·237	0·06	0·399
	60	5 300 000	3·8	8 900	5 340		0·12	0·242	0·071	0·433
	50	4 400 000	4·0	7 800	4 700		0·143	0·257	0·084	0·484
	40	3 520 000	4·2	6 500	3 900		0·178	0·266	0·106	0·55
	30	2 660 000	4·4	5 100	3 060		0·237	0·277	0·139	0·653
	25	2 200 000	4·6	3 750	2 700		0·287	0·29	0·169	0·746
	20	1 780 000	4·8	3 750	2 250		0·354	0·3	0·21	0·864

Note: With lower load factor than 50 per cent, cost could possibly be reduced due to reduction in operating staff.

TABLE C.

Cost of Current produced by Two 250-kW Reciprocating Sets (= 500 kW) with Two Lancashire or Water-Tube Boilers. Steam Pressure 160 *lb. per sq. in. (gauge); Superheat* 150 *deg. F.; Vacuum* 26 *in.; Coal* 12*s. per ton.*

Cost of generating and boiler plant (500 kW)	Load factor	Units produced per annum	Coal per kWh	Coal used per annum	Cost of coal per annum at 12s. per ton	Cost of labour for engineers and stokers per annum, including water and boiler cleaning	Cost per unit on capital at 12½ per cent for interest and depreciation (£1 625)	Cost per unit for coal consumed	Cost per unit for labour (£1 552)	Total cost per unit
	per cent		lb.	tons	£		d.	d.	d.	d.
Two 250-kW reciprocating sets; 2 condensers; main switchboard and coupling cables; power house; 2 30 ft. by 9 ft. 3 in. Lancashire boilers; boiler seatings and chimney; feed pump, steam and exhaust pipes, £13 000.	100	4 400 000	4·5	8 850	5 310	3 engineers and 3 stokers, 1 each shift, 1 ashman 1 shift, £26 per week, £1 352 per annum. Boiler cleaning and sundries, £200.	0·0887	0·289	0·0845	0·462
Annual charge for interest and depreciation at 12½ per cent, £1 625.	90	4 000 000	4·7	8 400	5 000	Total, £1 552 per annum.	0·0975	0·3	0·093	0·49
	80	3 500 000	4·9	7 700	4 600		0·111	0·315	0·106	0·532
	70	3 100 000	5·1	6 850	4 100		0.126	0·317	0·12	0·563
	60	2 650 000	5·3	6 100	3 700		0·147	0·335	0·142	0·624
	50	2 200 000	5·5	5 350	3 200		0·177	0·349	0·168	0·694
	40	1 760 000	5·7	4 500	2 700		0·225	0·368	0·213	0·806
	30	1 330 000	5·9	3 500	2 100		0·292	0·379	0·278	0·949
	25	1 100 000	6·1	3 000	1 800		0·354	0·393	0·338	1·085
	20	890 000	6·3	2 450	1 500		0·438	0·404	0·42	0·262

Note: With lower load factor than 50 per cent, cost could possibly be reduced due to reduction in operating staff.

TABLE D.

Cost of Current produced by One 1 000-*kW Mixed-Pressure Turbo-Generator with Receivers and Exhaust Steam Pipes. Steam Pressure* 16 *lb. Absolute* (1 *lb. gauge*)*; Vacuum* 27½ *in.*

Cost of generating plant with exhaust steam, receivers and pipes (1 000 kW)	Load factor	Units produced per annum	Coal per kW per annum	Cost of labour for engineers, assistants oil, water, and repairs	Cost per unit on capital at 12½ per cent for interest and depreciation (£2 250)	Cost per unit for steam, nil. Allowance must be made if H.P. steam used	Cost per unit for labour, stores, etc. (£1 000)	Total cost per unit generated	Exhaust steam used per kW generated
	per cent				d.		d.	d.	lb. per hour
One 1 000-kW mixed-pressure turbo-generator; 1 condensing plant; power house and crane; main switchboard and coupling-up cables; steam pipes; exhaust steam pipes; receivers made from old boilers; valves; grease separators.	100	8 800 000	Nil	3 engineers, 1 assistant, £16 10s. per week. Oil, stores, etc., £142.	0·062	Nil	0·027	0·089	35 approx.
Total, £18 000.	90	8 000 000	Exhaust steam available at all times	Total, £1 000.	0·068	Nil	0·029	0·097	37 approx.
	80	7 000 000			0·078	Nil	0·035	0·113	39 approx.
	70	6 200 000			0·087	Nil	0·039	0·126	40 approx.
	60	5 300 000			0·105	Nil	0·046	0·151	42 approx.
	50	4 400 000			0·124	Nil	0·055	0·179	44 approx.
	40	3 520 000			0·153	Nil	0·066	0·219	46 approx.
	30	2 660 000			0·202	Nil	0·09	0·292	48 approx.
	25	2 200 000			0·25	Nil	0·11	0·36	50 approx.
	20	1 780 000			0·31	Nil	0·13	0·44	52 approx.

Note: If coal used for make-up steam during hours exhaust available, the consumption and cost per kW can be obtained by reference to table of high-pressure turbo costs.

engine with flywheel and one Lancashire boiler 30 ft. by 9 ft. 3 in., including boiler seatings, etc., say £4 000.

Running cost per annum :

Capital cost £4 000	£
Depreciation at $7\frac{1}{2}$ per cent	300
Interest at 5 per cent	200
Coal	2 400
Stokers' wages, including ashmen and boiler cleaners, proportion only, say	300
Oil, stores and incidentals, say	100
	£3 300

Assuming 3 066 000 units required for the electric drive, it means that the comparative cost which could be paid for current would be :—

$$\frac{£3\ 300 \times 240}{3\ 066\ 000} = 0{\cdot}26\text{d. per unit.}$$

I have assumed in this case that the amount of attention required for looking after the engine would be the same as that in looking after the motor. It is usual to arrange fans in collieries so that they can be looked after by the compressor driver.

Air compressors.—The author refers to the use of air compressors and there is no doubt that compressed air is being used very largely in collieries, as in many pits it is impossible (or at any rate unwise) to put electrical machinery into positions where compressed-air plant can be installed. I refer particularly to coal-cutting, conveyers at the face, auxiliary haulages, main haulages, hand-drills, percussive coal-cutters, etc. The vertical types of compressor as made by Messrs. Belliss and Morcom and others are rapidly coming more and more to the front, and are undoubtedly most reliable and satisfactory pieces of machinery, lending themselves admirably to electric driving. It is undoubtedly desirable to have the compressors at the surface, as coal-cutters require clean air if they are to continue to work satisfactorily and it is often very difficult (if not impossible) to get a supply of cold water for cooling the air cylinders underground. In addition, the receivers, if underground, are very difficult to get into position. The synchronous type of motor is undoubtedly the best to use if there is any question as regards power factor, but supply undertakings, in some cases, do not raise any difficulty where the power factor is about 0·8, and under these circumstances slip-ring motors can be installed. I agree with the author that salient-pole motors can be adopted, but it is desirable under all circumstances to take this matter up with the compressor makers, so that they may design their compressor and the method of unloading, etc., to suit the motor. In a number of instances we have found it exceedingly expensive to run electrically driven compressors from an outside supply, and I give as an example what the approximate cost would be for operating an electrically driven reciprocating air compressor :—

·ty of compressor in cub. ft. per min. ..	5 000
·e h.p. of motor, say	1 000
·ning per annum, i.e. 16 hours per 270 days	4 320
Units per annum (1 000 h.p. × 830 watts per h.p. at 90 per cent efficiency × 4 320)	3 585 600
Cost per annum of 3 585 600 units at 0·75d. per unit	£11 205
Cost per annum of 3 585 600 units at 0·66d. per unit	£9 860
Cost per annum of 3 585 600 units at 0·5d. per unit	£7 470

In most cases it will be found much more economical to use steam for operating colliery compressors, and still more economical when the steam can be utilized in mixed-pressure turbo-generators. The following figures will make this clear :—

Assuming that a compressor of the size mentioned (namely, 5 000 cub. ft. per min., 75 lb. working pressure, and requiring 1 000 effective h.p. to operate it) is to be steam driven, this would involve a boiler plant consisting of two Lancashire boilers or one water-tube boiler, capable of evaporating 20 000 lb. of steam per hour and suitable for, say, 150–160 lb. pressure, complete with superheater and economizer, together with feed pumps and piping, steam pipes, suitable housing and a proportion of the cost of chimney, which I estimate at £7 000. The working costs will therefore be :—

Capital expenditure £7 000	£
Depreciation at $7\frac{1}{2}$ per cent per annum	525
Interest at 5 per cent per annum	350
Coal 4 850 tons, at 10s. per ton	2 425
Stokers, ashmen and cleaners, say	500
Insurance, say	50
Repairs	150
Sundries and incidentals	200
	£4 200

The current consumed per annum under similar working conditions would be :—

Units per annum [hours running (4 320) × 830 units per hour]	3 585 600
Cost per unit which consumer could pay to put steam and electricity on same basis $\left(\frac{£4\ 200 \times 240}{3\ 585\ 600}\right)$	0·285d.

The whole question, however, as to whether colliery fans and air compressors should be operated by electricity or steam, depends entirely upon the price at which supply undertakings can supply current, and in order to meet this condition I have (in many agreements which I have made for clients) called upon the undertakings to give the supply at varying rates for the following purposes: fans; main shaft pumps; air compressors; winding; and general work, including haulages, shop machinery, screens, etc. In addition to this, as supply undertakings are generally willing to give a night supply at a lower price than a day supply, separate and reduced rates are agreed under these circumstances.

Electric winding.—The author's description of electric winding (carried out, I assume, at the Powell Duffryn

Co.'s pits) is very interesting to me, particularly as I have been represented by a good many people as an opponent of electric winding. This is an entirely erroneous assumption, but I still maintain that whilst nobody appreciates how thoroughly suited electricity is for winding, it again resolves itself into a question of cost, not only for the electric winder itself, but more particularly the cost of operation. Therefore the use of an electric winder in preference to a steam winder depends upon the cost per unit at which current can be supplied to the winder. When I read my paper entitled "Electric Winding in Main Shafts considered Practically and Commercially," * I finished my reply to a very long discussion with the following words :—

"I admit, as I have done in the whole of my remarks, not only in this meeting but elsewhere, that there is a considerable field for electric winding in small collieries and for small outputs, but I do not think that when coal is cheap, and where the steam has to be generated at the colliery and the winding is heavy, electricity can compete.

"The general conclusions I draw as regards electric winding are as follows :—

"1. For small collieries there is a future for electric winding if the coal used under the boilers is of any considerable value.

"2. In large collieries there is a future for electric winding if the fuel or coal used under the boilers exceed 8s. to 10s. per ton.

"3. Electric winding cannot be economically applied in collieries for very large outputs where the horse-power required for winding is greatly in excess of the horse-power required for driving the other machinery, both on the surface and underground.

"4. In collieries generally, particularly those in which electric winding is adopted, colliery-owners will be well advised to take their current from the supply companies, assuming that they can purchase it at a reasonable price, even if this price is slightly in excess of what they can make the current themselves. The amount of capital required for the generating plant being so heavy, it could usually be applied to much greater advantage in increasing the electric plant or improving other machinery about the collieries."

Since I made these remarks (20 years ago) the cost of electric winders has fallen very considerably. The value of coal at the colliery has risen considerably above the figure at which I then based it, namely 8s. to 10s. per ton, and in addition supply undertakings—in order to assist the adoption of electric winding—have made considerable concessions in the cost of current for winding purposes. For moderate sized electric winders up to, say, 1 000 h.p., it appears to me that the simple winder with either plain drums with balance rope or semi-conical drums is the cheapest and (taken all together) the most efficient type of winder that can be installed, provided it is equipped with suitable control gear of the Allen West or similar type, with three-phase slip-ring motor. For larger winders it is necessary probably to adopt the semi-conical drum with d.c. motors and Ward-Leonard control, but this involves the use of a motor-generator with heavy flywheel, and I very much question whether the efficiency of this apparatus is any higher than that of the simpler type of winder and there are, of course, more links in the chain to go wrong.

Electric winders should not, in my opinion, be run at too high a voltage, and the winding in the stator and rotor, in the case of three-phase motors, should be so designed that only straight bars insulated with mica are used, so that repairs either to the rotor or stator can be very easily and inexpensively carried out. I have seen a very great deal of time and money lost due to high voltage being used on the winding motors, causing breakdowns and stoppages of the pits. My general views as regards the efficiency of the two types of winders can be gathered from the discussion on Mr. Heather's paper.*

I note that the author refers to a winding plant in a colliery in the Doncaster district (I presume he means Harworth) where they have installed an electric winder operated on the Ward-Leonard system by a high-pressure turbine with flywheel, attached to a d.c. generator. This system of winding is, I believe, claimed to be novel, but a proposition on precisely the same lines was put forward by me to a colliery (also in the Doncaster area) about 20 years ago.

Cost of the two steam winders at £6 000 ..	£12 000
The cost of electrical plant, consisting of two generating sets and two winders	£42 000

The total saving in the coal consumption per annum which could be shown at that date was £1 500, which was considered insufficient on an additional capital expenditure of £30 000, and the steam winders were finally adopted. At the present time it is becoming a standard practice in the Doncaster district, where there is no cheap supply of power, to install steam winding plants with mixed-pressure turbines, and also to use steam-driven compressors and fan engines, the exhaust steam being utilized in the turbines. I am fairly confident that this is the most economical scheme to adopt for isolated pits, taking everything into consideration. Of course, I refer to pits of, say, 800 to 1 000 yards in depth and with outputs of about 5 000 tons per day. These remarks do not in any way detract from the suitability of electrical winding for smaller pits and where the conditions are such that they can be economically used.

It would be very interesting if the author would give some particulars in connection with the generating plant at the collieries to which he refers, the cost at which current is being produced at the power station, and also the cost at which it is being charged to the various collieries under his control, because unless one has this information it is quite useless to attempt to decide whether steam winding or electric winding should be adopted. It appears, however (if the author's remarks apply to the Powell Duffryn Co.), that they have an excellent opportunity of producing in their own power station or stations a very large output of current at a very low price, by utilizing their exhaust steam in mixed-pressure turbines, using coke-oven gas and cheap and unsaleable fuel, and under these circumstances no

* *Journal I.E.E.*, 1906, vol. 36, p. 499.

* *Journal I.E.E.*, 1911, vol. 47, p. 609.

doubt the correct thing to do is to use electricity to the greatest possible extent. Some of the author's figures in connection with the operation of the winders approximate very closely to the figures which I assumed in my paper on "Electric Winding" already referred to.

[The author's reply to this discussion will be found on page 563.]

North-Western Centre, at Manchester, 3 March, 1925.

Mr. J. F. Perry: Speaking generally, I am in entire agreement with the views and facts expressed by the author. My own experience confirms the remarks he makes concerning the relative maintenance cost of Ward-Leonard and three-phase winders, and I have found in a large number of cases which have come under my observation that the Ward-Leonard winder is actually very much cheaper to maintain than the three-phase winder. On first thought this seems rather surprising when it is remembered that there are a greater number of machines involved. In practice, however, these machines give practically no trouble and in many cases under my notice have run for years without requiring anything more than the ordinary cleaning and oiling. In the case of a three-phase equipment the stator reversing-switch is called upon to handle heavy currents very frequently, so that it is not surprising that switch contacts and oil require frequent attention and renewal. In this connection it is interesting to note that the maintenance charges for air-break contactors are very much less than for the oil-immersed type of reversing contactors. Then, again, the liquid controller must be provided with a cooling system the tubes of which must be kept clean and free from sediment, and for certain classes of cooling water this feature involves fairly frequent attention. There are one or two points in the paper on which I do not see eye to eye with the author. For instance, I entirely disagree with him with regard to the synchronous motor for driving the flywheel equipments. On page 531 the author suggests that the installation of a synchronous motor to drive the Ward-Leonard equipments for the winders results in a lower operating cost than the common practice of installing flywheels. I cannot agree with the author that money can be more suitably spent in increasing generating plant and transmission systems rather than equalizing individual winding equipments. While conditions certainly exist where this might be perfectly true, the statement needs qualification, as it depends entirely on the proportion that the winder load bears to the total generating capacity of the system to which it is connected. The author identifies his statement with winding schedules raising large tonnages from a considerable depth. In my opinion that is probably one of the exceptions. Heavy fluctuating peaks should be isolated as near as possible to their point of origin, and the addition of a flywheel to the Ward-Leonard equipment will prove a more economical solution than an attempt to absorb the peaks in the power system generally. The actual efficiency, i.e. the kWh per ton hoisted, may be higher, but when viewed as a whole the cost per ton hoisted will certainly be less, as of course the peaks are not capitalized beyond the capital cost of the necessary flywheel. For the conditions outlined by the author I am of the opinion that the Stubbs-Perry scheme would prove more economical than either of the other two alternatives. Some time ago I carried out an investigation to compare the capital and operating costs of a power scheme for a group of eight collieries, (*a*) a central power station to supply power for all purposes, and (*b*) a Stubbs-Perry equipment on each winder, and a central station for the auxiliary load only. The winders in question were large equipments and the average input to the flywheel equalizer equipments was approximately equal to the auxiliary load demand at the colliery. Assuming one 7-hour coal-winding shift per day, the total annual operating cost of scheme (*b*) was 12 per cent less than that of scheme (*a*). For two 7-hour coal-winding shifts per day the difference was reduced to 9 per cent. It was apparent from the investigation that in order to be competitive with scheme (*b*) the load factor on (*a*) required to be 75 per cent, whereas the highest possible with a pure colliery load is about 60 per cent. The author's suggestion to increase the capacity of the generating plant, transmission lines, etc., on account of the peaks, tends to reduce the load factor still further and, apart from any question of capital, reduces the overall efficiency of the whole system. In schemes (*a*) and (*b*) the winders were equalized. If the flywheels had been omitted the capital charges would, I am sure, have been increased out of all proportion to the economies effected on the light-load losses of the wheels. Synchronous motors certainly have the advantage of power factor correction but would not, in my opinion, effect economies of sufficient magnitude to compensate for the interest on the additional capital required if the peaks are reflected on the generating plant. The economic principle underlying the Stubbs-Perry scheme rather emphasizes the foregoing point. The scheme was developed primarily to meet the case of the isolated colliery where winding from great depths was required and no bulk supply of electricity was available. Under these conditions electric winders could only be considered in connection with a power station, and it was not surprising to find that the initial capital cost put the scheme at a great disadvantage as compared with the more gradual development possible with steam engines and mixed-pressure turbines. The introduction of the Stubbs-Perry scheme makes it possible for the electrical manufacturer to compete with the steam-engine builders and offer a scheme which can be developed in easy stages without any reference to the future power scheme required by the colliery for the remainder of the load. By the addition of the turbine to drive the Ward-Leonard generators, winding can commence without any commitments as to a general power scheme, and is therefore financially comparable with the steam engine and mixed-pressure turbine arrangement from this capital

point of view. It has, however, one or two distinct advantages over the above scheme which might be enumerated as follows :—

Given favourable conditions it is cheaper in first cost to install, and unlike the steam engine and mixed-pressure combination the winder load is separated entirely from the remainder of the load about the colliery.

It is also possible to work in conjunction with public supply, the Stubbs-Perry winders relieving the power system of the big fluctuating peaks due to winding, and the power supply taking all the remainder of the steady running load about the pit.

The inclusion of an induction motor on the opposite end of the flywheel equipment to the turbine enables the alternative electric supply, whether from a public supply company or the colliery power station, to act as a stand-by to the Stubbs-Perry turbine and its boiler plant at the colliery. In the majority of cases this feature might also be used to advantage during the non-coal-winding periods as the turbine can be shut down, boilers at the colliery banked and the equipment operated as an ordinary Ward-Leonard equipment from the available supply.

From a large number of investigations I have made I feel convinced that even in the system described in the paper, Stubbs-Perry winders on some of the larger winding equipments would show up to advantage. I should like to ask the author whether the efficiency of 92·7 per cent given for the low-speed winding motor at the foot of page 529 has been verified on the actual machine, because this figure seems to be very high for this type of motor. Unless he can verify this figure his statement concerning the alternative method of gearing d.c. motors to the drum is, of course, misleading. According to the figures given in the paper the efficiencies are practically equal, the difference against a geared equipment being only 0·2 of 1 per cent.

Captain I. Mackintosh : The author has naturally taken the conditions at a large group of collieries, as the group with which he is connected is one of the largest in the country. When he talks of the all-electric pit he has considered it from this point of view, where he has plenty of generator capacity ; but from the point of view of a large single colliery the all-electric scheme has a serious rival in the mixed-pressure turbo set, which will entail winders, and probably fans, being steam-driven, to supply the necessary exhaust steam for the turbo. Of course the all-electric pit has so many advantages that where possible it is the ideal to aim at. Not the least important of its many good features are the ease and accuracy of obtaining running costs, because, if suitable instruments are installed, each particular unit of the plant can be checked and a thorough investigation made of any uneconomical unit in order to put it on a more economical basis ; and by these same instruments any alterations which may have been made can be proved beneficial or otherwise. While agreeing that motors of above 150 h.p. for pump drives should be normally of the wound-rotor type, I am using squirrel-cage motors of a much greater horse-power, and these are not giving any trouble. I should be glad if the author would say in what way he has found the auto-transformer starter so unsatisfactory for starting a pump motor. He is inclined to favour the steam drive to the electrically-driven compressor, but surely a synchronous motor-driven compressor would be a great help in improving the power factor of the system. Again, if the compressors are electrically driven and cutting is done on the afternoon and night shifts, they should be a great help in improving the load factor on the central station. The particular group of collieries with which the author is concerned has a central compressed-air station, with large air pipes going for miles up the Rhymney Valley, a point of interest being that all the joints in the pipe line are welded. I think I am right in saying that this system has given very satisfactory results, and that pipe troubles have been very few, at least until very recently, when a landslide broke up some of the pipes, causing the pits to be closed down for a few days. I have often considered that the ideal compressor job would be to have the compressor as near to its work as possible, in order that there may be as little risk as possible of loss in air pressure ; of course on the other hand it may have been proved conclusively that the central air station is a more economical scheme, and, if that is so, we should be grateful to the pioneers for having the courage to install this scheme. With regard to winding, there is no doubt that the Ward-Leonard system is the best method of electrical drive for avoiding heavy peaks on the central station, but there are so many links in the chain, the failure of any one of which would upset the output for the day. The a.c. motor reduces these links to a minimum, and on a large group of collieries the fluctuation caused by the operation of a number of such winders would probably cancel out, without affecting the central station. In addition, the Ward-Leonard set has a very low power factor, and the converter often runs for many hours on light load. The Ward-Leonard set has also the added advantage of being able to complete the wind by absorbing power from the flywheel if the supply fails. Although I regret to say so, I think that, even in these progressive days, the steam winder is more reliable than the electric winder, and in the case of breakdown could probably be more easily tinkered up to complete the shift. The author refers briefly to switchgear and points out that compound-filled gear will meet most requirements. There is no doubt about this. Compound-filled gear has, however, one serious drawback ; if it has to be dismantled a great deal of time is wasted in melting the compound, and if, on an emergency, it is necessary to remove the gear in quick time, the compound would be a great nuisance. Perhaps the author will say if he thinks it necessary to install gear of this description, or any type of flameproof gear on a screening plant at the surface of a mine, as are apparently required under No. 127 (iii or v) of the General Regulations as to the use of electricity under the Coal Mines Act, 1911.

Mr. G. A. Juhlin : The author places the limit on squirrel-cage motors at 150 h.p., mainly on the basis

that auto-starters are unsatisfactory. It is somewhat difficult to accept this as being a definite limitation on the size of motor of the squirrel-cage type. The company with which I am associated has 3 000-r.p.m. motors of 400 h.p. of the squirrel-cage type in operation. These have been running satisfactorily for eight or nine years. I think it would be a great pity to condemn the type of motor on account of the starter. The author, however, advocates the use of salient-pole self-starting synchronous motors, and has apparently had satisfactory results from this class of motor. It is to be presumed that his experience in this direction includes the type of synchronous motor for which auto-starters are used, and as some of these motors have an output of 1 150 h.p. it would seem that it is possible to obtain auto-starters which are satisfactory in service. With regard to the use of clutches, the author suggests the possibility of the use of a friction clutch. It seems to me that the synchronous induction motor provides a better solution in cases where the full-load pull-in torque is required, as with this type of motor it is possible to dispense with the clutch. Objections are sometimes raised that the air-gap of the synchronous induction motor is not as large as that of the salient-pole machine, but when it is considered that there are millions of horse-power of induction motors in satisfactory operation, there seems to be no reason for objecting to the synchronous induction motor on the score of the small air-gap, as this type of machine has in general a larger air-gap than the ordinary induction motor. It is interesting to note that the magnetic clutch is finding favour in the United States as a substitute for the ordinary friction clutch. The author refers to the salient-pole synchronous motor for driving compressors, and states that it was not until 1918 that it was considered suitable. I think that the reason which retarded the use of the salient-pole self-starting synchronous motor was that the electric supply undertakings would not permit this type of motor to be connected to their mains, owing to the starting current being high. In the United States this type of motor has been in general use for compressor work for many years, and as long ago as 1913 we actually supplied some motors for driving compressors for use abroad. In comparing the efficiency, the author claims an addition of 2½ per cent for the salient-pole machine, as against a synchronous induction motor. It is not clear whether the 93·2 per cent efficiency given for the synchronous induction motor is at unity power factor or at 0·9. The figure appears to be correct if 0·9 power factor is assumed, but in order to put it on the same basis as the salient-pole machine which is given at unity power factor, a figure of 94·2 per cent should be taken for the synchronous induction machine, which only gives an advantage to the salient-pole machine of 1½ per cent. The author also favours the salient-pole machine because it has been found possible to dispense with the bearing between the compressor flywheel and the rotor, due to the large air-gap. We have actually supplied synchronous induction motors with the rotor bolted direct to the flywheel. This of course may not be satisfactory in all cases. The figures given comparing the transmission of compressed air with electrical transmission are of great interest. I believe that similar comparisons were made when the compressed-air plant was installed on the Rand a number of years ago, and the conclusions arrived at were apparently similar to those at which the author arrives in the present case.

Mr. W. A. A. Burgess: It is not clear that the author fully utilizes the sensible heat of the coke-oven gases. That has been found at times to be a very appreciable amount of the waste heat available from coke ovens. With regard to his conclusions as to the burning of coke breeze and coke ashes, he appears to consider it necessary that medium volatile coal should be used to sandwich coke ashes. I have burned many thousands of tons of very fine coke breeze—so fine that it could be blown about—without the use of any other fuel whatever and have done so with chain-grate stokers of the underfeed type. It was found necessary to keep the fire between 9 and 10 inches thick to get the best results, and an efficiency of 56 to 60 per cent was obtained, dependent on the class of coke. Under these conditions the output of the boiler was somewhere about 66 or 67 per cent. We also obtained a large stock of washery settlings of high calorific value (13 000–14 000 B.Th.U.) when dry, but getting the moisture out was the great difficulty. It was found to be quite burnable in conjunction with coke breeze and appeared when dry to be a natural pulverized fuel, and I suggest it may be found possible to use washery settlings in this way. It was singularly free from dirt and really good coal in a very fine state of pulverization. My own long experience of compound-filled switchgear (17 or 18 years) has proved that its use has been amply justified in colliery working as well as in power supply under most onerous conditions. The charge of inaccessibility, so often levelled against metal-clad switchgear, is a myth. It is so made that accessibility, in the sense of access to live conductors, is entirely unnecessary, and the experience of renewal of the extremely small number of breakdowns in the whole of that period has proved that for renewal and extension it is in every respect as flexible as cellular gear and not nearly so dangerous. I have had considerable experience of power factor correction by means of Kapp vibrators, and from a sceptic I have been converted into a firm believer in their use. The particular case which I have in mind was for a 450-h.p. motor on compressor duty. This apparatus gave excellent duty for a period of six years to my knowledge, and required no attention other than the renewal of brushes. The author's remarks in regard to the similarity of compressor load and electrical load have been borne out by my experience in a large dye factory. They ran so closely that every extension of manufacturing plant was guaranteed to bring a similar extension of both services. I cannot entirely agree with the author's sweeping condemnation of oil-immersed contactors. My experience is that that is a matter of design entirely. I know of such contactors which have been in use for a large number of years on very heavy duty, and these have not given any trouble. Some of them have never been touched except for routine examination, and have never been renewed. That does not support the con-

clusion drawn by the author, but his conditions are admittedly onerous and he may not have been particularly fortunate in his selection. I certainly should not like to have in a colliery winding house or engine house an air-break contactor of the design shown operating on a 3 000-volt circuit either by solenoid or compressed air, more especially when the rest of the switchgear installed could be handled without danger. Excellent though the paper is in many respects, it rather belies its title. In my opinion it ought to have been entitled "Electricity on the Surface of Mines," for we are given very valuable information regarding the use of electricity on the surface but none regarding the use of electricity underground. The author appears to pin his faith to the use of compressed air below ground. Now although compressed air is quite suitable in very large bulk, when it comes to be applied to small apparatus and when welded joints cannot be used, the amount of leakage that cannot be detected by any means other than trying to add up the indication of the various metering units, all of them more or less unsatisfactory, is very remarkable. I think there is no need to-day to stress the point that it is perfectly safe to use electricity underground if reasonable care is taken. I am reminded, however, that such care is not always taken and I have seen a case recently of sound gear, sound motors and sound equipment generally, installed below ground—expensive plant and carefully protected cable—but with every cable gland left open to the access of moisture and air, and the gear left in such a condition that it could readily be flooded. One might just as well use compressed air bubbled through water into a bell-jar collector. If electricity is used below ground—and it is being increasingly so used—reasonable precautions need to be taken, and particularly with portable apparatus. The safe use of portable apparatus in mines demands the use of adequate interlocking systems. There are many ways of interlocking a switch with a plug device for a trailing cable so that a plug cannot be put in or pulled out, but when one comes to the motor end it is not so readily done, particularly if the coal cutter or conveyer, or whatever it may be, is some 150 yards away. To meet that condition Mr. Fisher, some years ago, introduced an electrical interlock which at the same time demonstrated the soundness of the earth connection. It had one drawback, however, in that he used full phase voltage to earth—through a resistance, it is true—for his interlock circuit. This meant that when the plug was withdrawn at the motor end it tripped the switch, but if the pilot socket should at any time be making a sufficiently good contact with earth through the body of a man a fatal shock might be received in the event of an attempt to close the switch at the far end, and an insufficient contact with an earthed rope or rail might permit dangerous sparking on a similar attempt. There is now available a similar device which operates in conjunction with an earthed pilot system and gives the desired interlock. There is a low voltage on the pilots, the general arrangement being practically the same as that suggested by Mr. Fisher, except that it embodies a small potential transformer. This system, which is covered by the Williams Rowley patents, is quite efficient but the potential transformer is an added complication and expense. There are now, however, at least two systems which give the required low-voltage interlock without the use of a potential transformer, one being manufactured by Messrs. Reyrolle and the other by Messrs. Switchgear and Cowans. These systems cost little to install and are of great use in mines and also on industrial plants, since they prevent the circuit being broken by a plug under any condition without first opening the main switch. They also definitely ensure that the earthing circuit is complete and perfect. It need hardly be emphasized that it is just as important to be sure that the earthing circuit is complete on industrial plants as it is below ground.

Mr. S. R. Mellonie: Referring to the use of autotransformers for starting synchronous motors, the author has certainly been unfortunate, and his troubles point to defective design. He states that the trouble was due to the arc drawn out from the "starting" contacts held on until the "running" contacts were closed, thus short-circuiting a section of the transformer. When describing the improved methods, he further states that step 5 "short-circuits the transformer." By reading between the lines the author's meaning is clear, but the wording is unfortunate. A method which has been used for the largest synchronous motors employs three oil switches suitably interlocked to ensure correct sequence of operation. The two switches controlling the transformer are tripped out by the operation of closing the main switch. Fig. 5 seems to make extravagant use of overload coils. These are shown coupled two in series and shunted by a time-limit fuse. An objection to this method is that one plunger invariably rises before the other, and the increased impedance so produced may overload the current transformer to such an extent that the resulting secondary current is insufficient to operate the second coil. A single trip coil operating through mechanism is a sounder proposition. The author mentions on page 534 the economical operation of Ward-Leonard sets having duplicate generators and duplicate motors by changing over the armature connections. This is a valuable feature of such equipments, and in a recent installation of two winders any of the four driving motors can be supplied by any of the four generators. This flexibility is obtained by the use of a few knife switches as, for the currents usual (2 000 to 4 000 amperes), plugs are not desirable owing to the difficulty of maintaining a good contact surface. The use of an automatic circuit breaker in the Ward-Leonard armature circuit is an undesirable feature. There appears to be a divergence of opinion on this question, engineers in some parts of the world insisting that the breaker is necessary, and others objecting to it as a dangerous and unnecessary device. The opening of the connection between the generator and the motor prevents the use of any form of regenerative control, and may leave the mechanical brakes in control during the lowering of an unbalanced load. Another alternative is to connect resistances across the motor armature immediately the armature breaker opens. This gives dynamic braking but introduces devices which do not "fail to safety." The

author's opinion on this matter would be a valuable contribution to our knowledge of the subject. Passing to the question of safety devices, one can certainly picture serious accidents due to the failure of this contactor or that small connection. The best policy would seem to be that these devices should be as few as possible, and that they should all fail to safety. Where that desirable characteristic is unobtainable, a second line of defence is justified. The additional cost of such protection does not appreciably add to the capital cost, as the switch and control gear for the average Ward-Leonard controller accounts for about 2 or 3 per cent of the total cost.

Mr. H. Green: One of the objects of the paper appears to be to attempt to disprove the idea that collieries generally are worked inefficiently, so far as the production of power is concerned. As of course the paper merely describes the collieries in which the author is personally interested, it only goes to prove his own particular case; but I think it will be agreed that the collieries mentioned are a very good example of efficiency. If, say, a municipal engineer were to look round the average colliery he would probably be appalled at the apparent waste taking place. He would, however, probably miss one point—that at many pits there is a quantity of unsaleable fuel which is sometimes difficult to get rid of. Therefore, obviously, it should be used for generating power; it would be ridiculous to install modern steam-raising plant for the purpose of saving fuel which is more or less useless. Therefore the old Lancashire boilers remain and give reliable service, and the fuel costs are very low actually. The great point, so far as colliery plant is concerned, is to install plant which will generate power from the most unsaleable fuel. The author gives comparisons for the generation of current by means of gas engines, or, alternatively, using the waste gas under boilers. As a result of experience I should say that, without doubt, the latter is the better method. Any increase of efficiency in the former is very much more than counterbalanced by the reliability and lower maintenance costs of the latter. In connection with the question of power factor correction, the future should always be taken into consideration in laying out a new colliery, and the judicious use of synchronous motors for driving d.c. generators and other plant is always an advantage. There are many instances where d.c. motors can be used with advantage, and this helps to justify the initial outlay for converting sets. I cannot help thinking that we have taken as granted alternating current for transmission, and in consequence the possibility of the generation and utilization of high-tension direct current is being neglected. The author mentions several types of switchgear and controllers. I think there is a field for the application of remote-controlled automatic gear. What I mean is that controllers and starters generally should be absolutely fool-proof. Knowing that often it is anyone's job to start a motor, it should obviously only be necessary to press a button and let the controller do the rest. A particular application of this would be on haulage gears. One man could easily look after, say, two or three haulage gears. Finally, I should like to emphasize what I consider to be a great mistake. We are apt to electrify a colliery piecemeal, by installing a motor here and a motor there. When this is done the resultant saving, so far as fuel consumption is concerned, is nil, because until at least sufficient motor load is added to enable a boiler to be cut off, the stand-by charges remain the same and the diminished steam requirement is not noticed. If any electrification is contemplated it should be of such a nature that a boiler or boilers can be dispensed with. As regards the comparisons between the electrical and compressed-air transmission of power, I hardly consider the figures are fair, because it is unlikely that the compressed-air system would be maintained at its initial efficiency. Nobody seems to worry about air leaks, but an electrical leak would soon assert itself and call for immediate attention.

Mr. A. B. Mallinson: I have used balanced jockey drives for many years and have found them exceedingly satisfactory. I should like to ask the author what power he has transmitted by them. The largest horse-power I have transmitted in ordinary industrial work was 150 h.p. when it was quite feasible to drive at 9 ft. or 10 ft. centres with a ratio of 6 to 1. When comparing the transmissions of compressed air and electricity the author takes 20 000 cub. ft. of air equivalent to something like 3 000 h.p. How would the table of relative efficiency be affected if figures were taken which are more applicable to the ordinary colliery—say 5 000 or 7 000 cub. ft. of air? I should like to ask the author how he expects the colliery proprietor to find the money to pay for equipments such as those shown on the lantern slides. Certainly many collieries to-day cannot find out of their own pockets even a fraction of the money required to install such plant.

Mr. S. C. Lloyd: A maintenance cost of £150 per annum is given in the paper for a set of oil-immersed reversing switches. I rather think the author is referring to the old type of hand-operated reversing switches. The present-day practice is to use reversing contactors, the maintenance cost of which is very small. The figure of £150 given for the reversing switches should be reduced at least to £30 for oil-immersed reversing contactors. Although the maintenance of air-break high-tension reversing contactors is considerably less than with oil-immersed contactors, the initial cost of the air-break type is about four times as great, so that even with the reduced maintenance cost the initial outlay of the air-break switches is not always justifiable, especially on the smaller equipments. With regard to the two types of controllers, the one with the moving electrolyte and the other with the moving electrodes, the moving electrolyte certainly gives automatic acceleration, and the paper clearly describes how this is done—by variation of the amount of electrolyte which passes through the electrolyte chamber. The other type, generally called the pot type, is simpler and not so costly in construction. The automatic acceleration of this type can also be obtained by means of an accelerating device which can now be supplied, so that we can use the pot type of controller to meet exactly the same conditions as the type in which the electrolyte is moving.

Mr. G. S. Corlett (*communicated*): It is interesting to note what rapid progress has been made in the electric mining industry during my own business experience. I well remember putting in, some 40 years ago, a small lighting plant at the George Pit (one of the many under the author's control) where the generator was a Gramme dynamo of about 2 kW capacity at 100 volts, and where all the details were very bad from a present-day standard. It is almost worth while to pause a moment to compare the conditions then and now: then, broadly speaking, there were no motors underground; to-day in round figures they total 1 million h.p. Then the technical knowledge available was minute in quantity and limited to the select few; now, as matters of everyday routine, oscillograph records of the starting current of motors are taken. The paper is obviously based on the conditions existing at the group of collieries with which the author is associated, and generally in South Wales, but these conditions are not to be found elsewhere. For example, the amount of gas given off there is enormous, and consequently the standard on which the amount of ventilation is based is the dilution of this gas to a sufficient extent to render it harmless. In many districts the amount of gas given off is so small (there are still many pits worked with naked lights) that the standard of ventilation is entirely different, namely, sufficient to provide a cool and healthy atmosphere for the workmen. A good many years ago I obtained the following figures relating to a Welsh colliery which is now, but was not then, controlled by the author's company: Ventilating current 300 000 cub. ft. per min., percentage of gas in the main return never less than 2½. This means that not less than 7 500 cub. ft. of free gas was given off every minute, and often more. Under such conditions it would be an act of criminal folly to reduce the fan speed at the week-ends. On the other hand I find it quite a safe commercial proposition, in many collieries where I am buying current, to reduce the fan speed during the week-ends and holidays, and obtain an appreciable saving in costs. The author gives under certain specified conditions 32 units as a reasonable consumption per ton of coal raised, and he allows 20 units out of these to furnish the necessary compressed air. In large numbers of collieries within my personal knowledge there is either no compressor at all or only a small one for operating rock drills and the like. At the moment I cannot put forward figures applying to some other district, but I know that they would be widely different. The paper suggests by its whole tone that the real problem of supply to collieries is narrowed down to two aspects of the case: (*a*) Complete electrification with high-pressure turbos, and (*b*) partial electrification with mixed-pressure turbos. A third alternative, and one which has increased and is bound to increase still further, is the public supply, and, in the case of the smaller collieries and single ones, such a supply is appreciably cheaper than a private supply. The convenience alone of being able to switch on any individual motor when wanted, without reference to any other plant, is often sufficient under certain circumstances to justify the preference. It must, of course, be remembered that groups of collieries of the magnitude and extent as the author's are few and far between, and probably nowhere else in Great Britain would be found another group where the same amount of generating and transmission plant would be required or justified. In a great majority of cases the groups are small, and there are very large numbers of individual pits, some large, some small, but in my view very many of these could be best furnished with power from the public mains. Nevertheless I freely admit that in no branch of engineering is it more dangerous to dogmatize; each individual case must be considered on its merits. In conclusion, I should like to point out that many of the problems—such as whether electrification shall be adopted or not, and if so to what extent—are determined not by engineering considerations, the estimated savings per annum or the other advantages that would accrue, but by finance conditions only. The average loss per ton of coal raised in Lancashire, Cheshire and North Wales for the last quarter was approximately 11¼d., and it is not difficult to understand the reluctance of colliery proprietors to spend money. If, as is often the case, there is only sufficient capital available to equip the interior of the mine, then obviously the supply must be obtained from an outside source.

[The author's reply to this discussion will be found on page 563.]

North-Eastern Centre, at Newcastle, 9 March, 1925.

Mr. S. A. Simon: The paper, together with the discussion, should show what may be considered to be the best present-day practice, and should indicate the trend of further development and formulate the more immediate questions which electrical engineers will have to solve in the interests of mining. As electrical engineers we are, I suppose, all in agreement with the author's conclusion—that the electrification of the whole of the machinery at a colliery can be proved to be a sound commercial proposition. The figures given by the author, and other similar figures which may emanate from the discussion, should be of very material assistance to the electrical engineer in carrying his points. The great need of the coal-mining industry in this country at present is reduction of cost, particularly of the cost of labour. Means must be found of increasing the output of coal per man employed, and it is the task of electrical engineers to devise the means by which electricity can assist in this consummation. This should be constantly kept in view so that the record of the discussion may be of the greatest value to electrical manufacturers and contractors, as well as to those actually engaged in the operation of the mines. It seems to me that the tables in Part 3 of the paper require amplification. In comparing steam-driven with electrified collieries, comparisons are made of the percentage of coal raised used for power on the one hand, with kilowatt-hours per ton on the other. I have

endeavoured to bring this comparison to a common denominator. To do this I must assume a coal consumption per kWh. I have first assumed 3 lb. Taking Table 8 I find that initially when raising 4 650 tons per week the equivalent coal consumption was 6·97 per cent. After the steam compressor was shut down the equivalent coal consumption was reduced to 6·79 per cent, and after the fan engine was electrified the equivalent coal consumption was further reduced to 5·6 per cent for the same output (4 650 tons) of coal. After complete electrification the equivalent coal consumption was increased to 7·68 per cent with an increased output to 5 700 tons per week, and the hypothetical consumption for this output with the original steam plant supplemented by electricity would have been 10·68 per cent. If a smaller equivalent coal consumption per electrical unit is assumed, the figures work out correspondingly more favourably for electrification. The most significant point is that after complete electrification, with an increased coal output, the percentage consumption is increased. The paper shows that more compressed air is used for conveyers and other air engines. This will doubtless account for the whole increase, but presumably there will be considerable saving in labour costs, and some indication should be given of the comparative value of such saving to set against the increased power consumption. I should imagine that it would be more than a mere reduction of unskilled labour at the pit head. May we take it that the increased output of practically 25 per cent was obtained without increasing the number of men employed? Table 5 when treated on similar lines shows a marked economy for electric drive, viz. 3·75 per cent equivalent estimated consumption with electrified winder against 5·53 per cent with an all-steam drive. It is not clear what is meant by the sub-heading "Present Conditions" in this table. Table 6 shows a very marked economy of electric winding compared with steam winding, and Part 2 of the paper shows that the electric winder has thoroughly justified its use. The system in which the exhaust steam from the steam winder is utilized in a turbine can only be considered for isolated cases and during transition periods. A very strong case has been made out for the Ward-Leonard winder without power-equalizing flywheel. With increasing capacity of generating plant this is a more or less expected result—as the peaks will be of comparatively less account—and, moreover, it is probable that in new pits the whole winding cycle is being laid out for the most advantageous electrical drive, whereas in earlier electrifications the electrical equipment had to be made to suit conditions which were essentially laid out for steam winding. It is interesting to observe the large proportion of power used for compressed air in South Wales pits. Naturally the figures for this district with shallow mines, where there is no objection to using electricity at the face, are very much lower. I have seen figures as low as 8·46, and for a large group of Durham pits with a moderate amount of water the figure works out on an average at 11·54. Other figures are 6·9, 10 and 13·5. No doubt if compressed air could be replaced by electrical drive in South Wales the figure of 20 units per ton would be reduced to 6 or 7. I appreciate that conditions in South Wales are such as practically to preclude electricity in places where compressed air is now used, and I am not one to advocate the indiscriminate use of electricity in places where Regulation 132 applies. On this account, therefore, I can understand the omission of any reference to electrical coal-cutters, face conveyers, etc. At the pits with which I am connected, electrically-operated face conveyers have been in use for many years and their use latterly has been considerably extended. They are of the scraper type driven by 9-h.p. squirrel-cage motors through Hele-Shaw friction clutches and chains. I am somewhat surprised, however, that no mention is made of main haulages amongst the more important loads to be dealt with. Main and tail type haulages are largely in use, and the methods of drive have not changed essentially from the types installed 15–20 years ago. I have found that a rope drive has worked very satisfactorily both above and below ground, and I now favour this arrangement in preference to direct gear. For larger haulages at medium pressures, contactor-type stator reversing-switches have lately been used with much success, although in the earlier types with large low-speed motors trouble was experienced on the blow-outs. The use of contactor reversing-switches has both lightened the labour of the attendant and reduced the heavy cost of upkeep of reversing controllers on larger motors. The rotors are controlled by means of liquid starters. Turning to power factor correction, I am inclined to agree with the author that in new installations synchronous motors are probably the best means of obtaining the requisite leading wattless kVA. It is particularly interesting to learn that such motors have been applied to Ward-Leonard winders, and if this is really satisfactory there should be a wide scope in this direction on large systems. A certain amount of prejudice has arisen against the use of synchronous motors for driving fans, due to the difficulty of starting of some early types of salient-pole machines. The synchronous induction motor has overcome this difficulty. In cases where the installation is complete, and suitable drives for synchronous motors are not available except by scrapping existing induction motors, the electrostatic condensers are eminently suitable and give satisfactory results. An advantage is that they can be obtained in small units and placed close to the motors the power factor of which is to be corrected. I am informed that in certain pits each small motor is provided with its own condenser, and the air-gap is made very wide. In regard to the power station, an eminent mining engineer, recently speaking of electrical costs, ruled the private generating station altogether out of consideration, and, basing his arguments on the rates usually charged by the supply undertakings, he maintained that it was more profitable to drive the winder, fan and compressor by steam. I think that the author has amply justified the private generating plant, and along with it the complete electrification of the above-named capital units of plant, but a little more information would be desirable in regard to load factor, cost of production, etc. This discussion should prove the economic possibilities and limitations of the private station. One peculiarity of the colliery generating station is its ability to utilize

all sorts of fuel and particularly the low grades. The time may come, however, when the supply undertakings may have to take low-grade fuels from the collieries, as a consideration for the collieries taking a supply.

Mr. S. Burns: I was rather surprised to hear the author state that in his experience the energy consumption per ton of coal raised by means of an a.c. geared winder is usually found to be appreciably in excess of the estimated energy consumption. Such is not the case in this coalfield and one wonders why it should be so in South Wales. It may be that there is a disparity in the weights of conveyer-filled and hand-filled tubs, with a consequent variation of the net unbalanced load from time to time, but this should not present difficulty where the torque/time cycle is arranged to take account of the heavier lift as a normal condition of working. The disparity in weights cannot be great, and it follows that the braking peaks when lighter loads are being decelerated cannot differ appreciably from the braking peak of the normal winding diagram. The author has mentioned the Stjernberg coefficient and the correction to which recent improvements in winder design have rendered it subject. That formula is related primarily to cylindrical-drum winders operating with tail ropes of a weight per unit of length equal to that of the winding rope and so is equally applicable in the case of winders operating without tail ropes, but where the drum profile has been arranged to compensate for the effect of overhang of the winding rope throughout the winding cycle. It is a formula which may only be applied with circumspection in the case of other arrangements of drum profile and, what is more important, it neglects to take into account the economic aspect of the problem. It is no sufficient justification for the choice of a particular type of winder that it can be shown to be the most efficient arrangement in terms of energy consumption per trip. What is required is the arrangement of plant which will be most economical in terms of total winding cost per ton of coal raised. The energy consumption bill is an important item, but so also are Imperial taxes, local rates, interest, depreciation, insurance, inspection, maintenance and stores. For example, I recently took out a set of "average" winding conditions for Northumberland and Durham. The average value of B is $0 \cdot 167$ and the Stjernberg coefficient, therefore, serves as an indication that an a.c. geared installation is likely to be satisfactory. The coefficient does this but no more. Given a schedule of definite winding data, it is not difficult to decide which of four or five alternative arrangements of plant is the most economical, but the problem seldom presents itself in so simple a fashion. There at once arises the question as to whether it will be better to install a complete new winder, probably to the rear of the existing winding engine, or whether the existing mechanical parts should be converted to electric drive. At this stage there may be complication because, whereas with the new winder one is free to determine suitable drum dimensions, it may well be that the dimensions of the existing drum are such as to render a direct-current motor and Ward-Leonard control desirable. This is not an exaggerated statement of the problem and my object is to show that close reliance cannot be placed upon the Stjernberg coefficient when a choice is to be made upon economical grounds in circumstances which are to be met regularly in everyday practice, if rarely in technical analyses. It is proposed shortly to install in this locality an a.c. geared winder, although the value of B is $0 \cdot 358$. The circumstances are similar to those I have described and it would be difficult to imagine a case more likely to be favourable to Ward-Leonard control upon the score of relative efficiency (for the value of B is high). Similarly the Ward-Leonard control alternative is likely to be favoured in respect of capital cost and, therefore, of annual capital charges (for the cost of the complete new a.c. geared winder with bicylindro-conical drum is naturally somewhat higher than that of the electrical equipment only of the Ward-Leonard conversion alternative). As a matter of fact the Ward-Leonard arrangement is only more economical than the a.c. geared plant in the ratio of $1 \cdot 31$ to $1 \cdot 29$. The difference is so little that the final choice may well be influenced by some local circumstance of no importance in itself—in this case a matter of convenience only—and which certainly is not taken into account by the Stjernberg or any other formula. The author mentions the Harworth main winder in particular. This plant is arranged upon the Stubbs-Perry principle and also embodies Ward-Leonard control, but it is not to be supposed that because it is a Stubbs-Perry winder it must of necessity be a Ward-Leonard-controlled winder. Briefly the Harworth main equipment embodies a turbine, gears, flywheel, d.c. generator and d.c. winder motors, but the Stubbs-Perry principle would still apply were the equipment to comprise turbine, gears, flywheel, three-phase alternator and three-phase winder motor. With the latter arrangement the alternator and motor would, of course, be solidly electrically coupled, and in such a case the variation of frequency consequent upon flywheel speed fluctuation is not a matter of inconvenience, since this can quite well be taken into account when plotting the speed/time cycle of the wind. I think it will be found that the value of B for this winder is $0 \cdot 291$ and I have sometimes wondered why an a.c. geared installation was not chosen. I do so still in view of the author's statement that in the case of two large a.c. geared winders at present being installed in this country the value of B is $0 \cdot 292$. The author's experience with tail ropes has been unfortunate and is a disappointment to those of us who hold to the view that these should be employed upon every occasion where their use can be shown to be beneficial to the energy diagram. There is much to be said for them even in conjunction with drums of special profile, for if by that means the ratio of larger to smaller diameters of the drum can be reduced, then appreciable reductions in weight and cost will result.

Mr. R. W. Mann: It is interesting to note that the author obtains such a very high efficiency from the belt drive of fans with jockey-pulley arrangements, and I should hardly have expected that this arrangement would have given such results as to have been equal, let alone superior, to a high-class helical-gear reduction, the efficiency of which might be anything from 94 to 98 per cent, depending upon the type of gear. The author refers several times in the early portion of the paper to the comparative advantages of the syn-

chronous motor of the salient-pole type, with or without pole-face windings, as against the synchronous induction motor. As he states, this question has been dealt with in earlier papers read before the Institution, the discussions on which appear to show that the synchronous motor was slightly more efficient than the synchronous induction motor, and, while this is true, it would appear to me that too much consideration can be given to these problematic little differences in efficiencies, even on continuous running plant, and more particularly plant which is not constantly fully loaded, e.g. colliery plant. Take, for instance, Fig. 1. The sizes of the machines are not given, but from the curves I should expect them to be about 450 kVA, the comparative efficiency of the synchronous induction motor being 1 per cent lower, as is usual for machines of this size and upwards. This lower efficiency is almost entirely due to the extra losses in the secondary winding caused by the larger mean turn of the coils than those of a salient-pole machine. It follows, therefore, that at low loads (with constant power factor and hence reduced excitation) the efficiency becomes almost the same as that of the salient-pole machine. The author states that the advantages of the motor shown in Fig. 2 are (1) higher efficiency and (2) normal voltage excitation. The first I have dealt with, but I do not quite follow the line of argument with regard to the latter. Owing to the series-parallel arrangement of the d.c. windings it is quite probable that the excitation voltage would be somewhat higher than that in the case of the synchronous induction motor, but not very much, due to difficulties of design, say, between 35 and 40 volts as against say 25 on a synchronous induction motor. There is, so far as I can see, little advantage to be obtained from the higher voltage. I should be glad if the author would say what is the excitation on this particular machine. The motor has certain disadvantages not mentioned by the author, viz. (1) extra complication, including a switch on the rotor for altering the windings from the starting to the running position, and (2) the machine is an expensive one for British manufacturers to build, costing considerably more than the synchronous induction motor. This fact is not, perhaps, obvious because of the advantages which accrue to our foreign competitors due to cheaper labour and material. Whilst the actual reliability of the two types of machine may be very similar, the author himself refers to a greater possibility of trouble with the starting gear of a salient-pole synchronous motor than with that of a synchronous induction motor which, after all, differs practically not at all from the ordinary starting gear of a slip-ring induction motor with which colliery staffs have more experience. There is, however, another, and to my mind very important, advantage of the synchronous induction motor over the salient-pole machine, and that is that while in both cases as compared with a slip-ring motor there is an additional link caused by the necessity of the d.c. exciter for the field, with the salient-pole machine, in the event of a breakdown on the exciter, the complete unit is useless. With the synchronous induction motor, however, the unit can be run as an ordinary slip-ring induction motor without any d.c. excitation at all, the only limit to this application being where the lagging power factor of the machine as an induction motor is lower than the corresponding leading power factor for which the machine was designed. This is, however, very rare, as most synchronous induction motors are built for at least 0·8 leading power factor at full load, and the power factor of an induction motor is not likely to be less than 0·8 lagging. Quite apart from the above, a synchronous induction motor complete with its switchgear is cheaper than a salient-pole machine complete with its switchgear, and it is a case for serious consideration whether the problematic saving in efficiency justifies the additional cost of the dearer machine. Dealing now with electric winders, it would appear that the author is of the opinion that for single, deep mines electric winding may not be justified, presumably on account of the relationship of the peak load to the rest of the colliery load. This difficulty can, however, be overcome by the application of the turbine-driven Ward-Leonard system which the author describes later in his paper. The larger the winder, the greater the economy over a steam winder, which is the other alternative. The author drew attention during the reading of the paper to the fact that, on the turbine-driven Ward-Leonard winder which he describes later, a second equipment had been ordered, and that it had been found necessary to add an induction motor to the end of the motor-generator set of the second equipment. This is not the case. It will be apparent from a consideration of the scheme that external braking must be provided, regenerative braking only being possible to that extent necessary to bring the flywheel up to full speed and no more. To effect the necessary braking, it is possible to consider either a water-wheel brake or an eddy-current brake similar to that which was fitted to the first equipment and which has given every satisfaction, or an induction motor provided with d.c. excitation. This latter arrangement has been adopted in the second equipment, due not to the disadvantages of the eddy-current brake but to the advantages of the induction motor as a brake, inasmuch as the power system at this colliery has now developed and the induction motor can be used as a stand-by to run the motor-generator set for light-load winding or occasional trips without the necessity of starting up the turbine and flywheel. I fully agree with the author that comparative costs favour electric winders and high-pressure generating plant as against steam winders and mixed-pressure generating plant, and I endorse his view that where power is available from a supply undertaking at reasonable rates, taking everything into consideration, still greater economy can be shown for electric winding. Referring to a.c. versus Ward-Leonard, Stjernberg's conclusion, from his mathematical analysis, was based upon the point of his graph where the value of MS/QT^2 was such that no braking was necessary. This does not necessarily represent the dividing lines between the a.c. and Ward-Leonard systems, and with Stjernberg's own diagrams I should not, under certain circumstances, consider the braking excessive resulting from a value of $MS/QT^2 = 0\cdot3$ with $V \div S/T = 1\cdot5$. To my mind, the tendency of to-day is to use a.c. winders right up to the limit where the respective efficiencies in conjunction with the respective capitalized charges

make the Ward-Leonard an economic necessity. With regard to a.c. motor speeds, the inertia referred to drum varies as (gear ratio)^2 and, whilst of course it depends upon individual designs, I find that the inertia of the rotor drops in roughly the same ratio within reasonable limits. With modern gearing, therefore, there is no harm in using higher-speed motors than those which the author gives, with their consequent better performance figures and lower capital cost. Whilst I agree that a.c. winders do not have the same delicacy of control as Ward-Leonard winders, I am convinced from a fairly wide experience of a.c. winders that, within the limits of their economic application, the control with or without reverse-current braking is all that can be desired for ordinary service. Dealing with the question of braking on a.c. winders, whilst there are, of course, occasions where excessive braking necessitates the use of reverse power, one finds that these cases are the exception rather than the rule for the conditions which prevail in Northumberland and Durham, and normal methods of braking, i.e. wooden brake blocks or patent fabrics, have given quite good service. The following figures are the averages taken from a number of local steam and a.c. winders, from 2 to 500 h.p.

System	Average life of lining	
	Wood	Ferodo
Alternating current . .	2–3 months	12–18 months
Steam.	3–4 months	18–24 months

With regard to the controllers for a.c. winders, it is now possible to incorporate the advantages of automatic acceleration with the advantages of flexibility for manœuvring of a metal-pot type of controller, and I should say that it is very doubtful whether the weir type of controller will be used in future modern equipments. The author's method of indicating reverse-current power is ingenious and interesting. I do not agree with him that even in small winding equipments direct-operating reversing switches are satisfactory. I have seen many types of such switches and I consider that any reasonable increase in cost is a very good exchange for the reduced manual effort required to operate contactor-control reversing switches. When mentioning the automatic control of Ward-Leonard winders, I presume that the author is referring to semi-automatic control given by cam-operated gear—the present-day practice. The question of complete automatic control has been given much consideration, and as far as I am aware there is no completely automatic winder in existence. There would appear to be two chief considerations in the design of an automatic winder—advantages and engineering difficulties. The first is a question of the Coal Mines Act, and I should imagine it doubtful whether permission could be obtained for a locked-up winder house and for the cages to be controlled from bank by the banksman; without such saving it is difficult to see the advantage. Were there any possibility of such permission being given, then I imagine that greater attention would be paid to the engineering difficulties, the chief of which would appear to be double-decking and the design of a motor which would have an exact straight-line characteristic of speed against load during the slowing down of the motor to rest, essential for repetition decking with varying loads. In short, the cam control of a Ward-Leonard winder might perhaps be called an emergency measure eminently desirable but having its counterpart with arrangements that can be and are regularly made for a similar effect on an a.c. winder. The author refers to high- and low-speed d.c. machines, and I can assure him that quite a definite commercial case has been made out for higher-speed d.c. motors on Ward-Leonard-controlled winder equipments. When one takes into consideration, using the author's own figures, that the low-speed motor without gear is only 2 per cent more efficient, while the overall efficiency of the winding cycle may be round about 60 per cent, one really must agree that commercialism must be given room, especially as it can show a very large difference between the capital cost of the low-speed d.c. motor and a high-speed d.c. motor plus gears, the latter being the cheaper. With regard to the maintenance of the additional bearings, my experience is that there is little or nothing in it, and I am in agreement with the author when he says later in his paper that high-speed bearings appear to run indefinitely. The author's comparison between a Ward-Leonard and a Ward-Leonard–Ilgner winder is interesting. It is, however, to my mind impossible to make a generalization from one special case—the application of either of these systems is one necessitating a close study of particular conditions. While agreeing with the author as a general principle that the generating plant should be increased in preference to installing an Ilgner set, there are many cases where it is impossible, and also many cases where the necessary supply network to keep voltage-drop due to peaks within reasonable limits makes the Ilgner set an economic necessity. It is difficult to analyse Table 4 without many more particulars, but there are one or two outstanding features. The motor driving the motor-generator set is of 3 250 h.p., the corresponding peak being approximately 4 000 h.p., or 1¼ times; a system which will take a 3 250-h.p. motor obviously does not require the help of a flywheel for a peak load 1¼ times the rated load. In the next case the motor driving the motor-generator set is of 2 000 h.p., and even with a flywheel the peak is 3 800 h.p., or 1·9 times the normal, so that if the flywheel is doing any equalization at all, the peak without it may have been 2½ times. In the light of the foregoing remarks, this is a case where a flywheel is probably needed. The comparative overall efficiency conveys practically nothing, due to the different net loads. I had a case recently where an extra deck, adding two tubs of coal to the net load for the same output, resulted in halving the size of the equipment put in, with a consequent saving in overall efficiency and cost. It follows that two winders with net loads of 6 and 7½ tons respectively cannot be fairly compared. With regard to balance ropes, in the early days there was a certain amount of opposition to their use, undoubtedly due to steam-

winder experience. Now, however, their use has been demonstrated to be satisfactory, even on cylindro-conical drums, provided a suitable rope suspension shackle is used, with the result that I have no hesitation in suggesting their use where the resulting economy warrants it. The application of the Koepe system in this district in four cases has done much to bring about the foregoing result. The author supplies some valuable data when he gives the actual steam consumptions of modern steam winders. A certain amount of data exists for older winders, but the figures put forward by the manufacturers of modern steam winders are undoubtedly optimistic when compared with the author's figures. In conclusion I should like to say that I prefer the straight a.c. winder for every possible case where it is an economic proposition. There are close on a hundred such plants in this area and I feel that it is on these lines that the coal industry can be best served as a whole.

Mr. A. B. Maclean: In Table 2 the author gives some average figures for the current consumption per ton of coal raised at a modern colliery, and, as he points out, the figures apply specifically to South Wales conditions. It may therefore be of interest to give similar figures for collieries in the Northumberland and Durham coalfield. In Table E such figures are given with information as to some of the essential features governing the total consumption. The figures in this table are derived from meter readings taken over 12 months, three meters being used on some of the circuits and the mean value taken. Accurate coal output and pumping figures have been obtained from the collieries. It has not been possible in all cases to get meter readings to give a complete subdivision of the units, but estimated figures in those cases where meter readings were not obtainable are given in Table F.

TABLE E.

Consumption of Current for Completely Electrified Collieries.

No.	Output,* in tons per day	Depth	Ratio † of water to coal	Consumption, in units per ton					Remarks
				Ventilating	Pumping	Winding	General supply	Total	
		ft.							
1	637	800	1·2	1·27	1·00	2·23	3·66	8·16	Moderate amount of compressed air used
2	1 073	478	1·8	2·07	1·41	4·20		7·68	No compressed air
3	940	720	1·37	2·47	1·11	3·32		6·90	No compressed air
4	4 650	1 170	3·12	—	—	—		21·5	Group of 6 pits. Large amount of compressed air used

* Actual total outputs for the year 1924 have been taken and divided by 250.

† Ratio of total tons of water pumped to total output in tons of coal.

The units per ton given under the heading "General Supply" include the current taken by the compressors used in cases 1 and 4. It will be noted that in cases 1, 2 and 3 the total consumption per ton is very much less than the figures quoted by the author for South Wales. This is due mainly to the shallower shafts and to the fact that in case 1 very little compressed air is used, and in cases 2 and 3 none at all. In case 4 the consumption is relatively high owing (1) to the greater depth of shaft, (2) to excessive pumping, and (3) to the large amount of compressed air used.

TABLE F.

No.	Ventilating	Pumping	Winding	General supply	Total
1	1·27	1·00	2·23	3·66	8·16
2	2·07	1·41	1·32	2·88	7·68
3	2·47	1·11	1·99	1·33	6·90
4	4·27	5·14	3·21	8·88	21·5

[**Mr. W. C. Mountain** also took part in the discussion. The substance of his remarks will be found on page 538 in connection with the discussion before the Institution.]

[The author's reply to this discussion will be found on page 563.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 11 MARCH, 1925.

Mr. W. W. Wood: So far as the technical points dealt with in the paper are concerned, I am in agreement with what the author says, but I must criticize his statement that there are very few cases where the mixed-pressure steam-winder plant can compare favourably with an all-electric plant. His own figures in Table 5 show that, whatever may be the result at the Powell Duffryn Co.'s collieries, in very many collieries the steam winder and mixed-pressure turbine would be the best commercial proposition. In Table 5 there is a comparison between the number of units of electricity required to supply a colliery with an electric winder, and the actual amount of steam used to supply both a steam winder doing the same work and a mixed-

pressure turbine generating electricity. The units generated by this mixed-pressure turbine are given and we therefore have sufficient data to compare the amount of coal used in each case, provided we know how many pounds of coal are required to generate one electrical unit. Unfortunately, the author does not give any particulars enabling me to estimate either his cost of electricity or the pounds of coal he requires to generate 1 kWh—presumably at the Powell Duffryn Co.'s collieries the latter is a very low figure and one that could very seldom be obtained by any other group of collieries. We cannot tell, therefore, what the financial results of electrifying the winder would be at the Powell Duffryn collieries, but we can see from the author's figures what would be the results at an average colliery. The average amount of coal used for the larger generating stations (exclusive of the three largest) of this country for 1924 was about 3 lb. of coal per unit generated. An average colliery may be able to do better than this, though generally the results are not so good. I have, however, assumed that $2\frac{3}{4}$ lb. of coal is required to generate one useful unit, and by this I mean a unit which can be used for driving the winding gear or other productive plant, and not including the units required for condenser, auxiliary apparatus or loss in transmission. The total units generated will be considerably in excess of the useful units and I think that the figure of $2\frac{3}{4}$ lb. of coal per useful unit is as good as can be expected in most collieries, as a normal daily performance. On this basis, taking the author's figures we get the following results:—

Total high-pressure and low-pressure steam required to supply both the steam winding engine and the mixed-pressure turbine (author's actual figure) per hour ..	58 000 lb.
Total ditto required per week of 42 winding hours, 58 000 × 42 equals ..	2 430 000 lb.
Coal required per week to generate the above steam (based on the figures on page 534)	332 000 lb.
Units per week generated by waste and live steam from the above coal in addition to the winding	86 000
Of these units apparently all were not available for useful work, and these we have to deduce from further figures as follows:—	
In Table 5 the total units generated by the mixed-pressure turbine are given as	86 000
Plus units from an external supply ..	11 150
Total	97 150
These were necessary to supply the colliery washery, etc., while if the winders were electrified the author gives the units required for the washery as	90 000
	7 150
By subtraction we see that 7 150 units were apparently used for the turbine auxiliaries and that the useful units supplied by the mixed-pressure turbine were 86 000 — 7 150, equals	78 850

If the steam winder were replaced by an electric winder, it would be necessary to supply from an external source 78 850 units, which were previously obtained from the mixed-pressure turbine, in addition to the units required for the winding gear. The total units therefore required would be:—

Electric winder (author's figure)	52 500
Extra units owing to shut-down of mixed-pressure turbine	78 850
Total additional units required ..	131 350
Coal required per week to generate these units on the basis of 2·75 lb. of coal per useful unit	361 000 lb.
Extra amount of coal required per week to supply the colliery if electric winder is used as compared with steam winder and mixed-pressure turbine, is 361 000 — 332 000	29 000 lb.

We see from the above figures that if it requires $2\frac{3}{4}$ lb. of coal to generate one useful unit, then the substitution of an electric winding gear for a steam winder and mixed-pressure turbine, in the case cited by the author, would involve an extra coal consumption of about $12\frac{1}{2}$ tons per week. In addition to the extra coal there would be of course a considerable cost per annum in the interest and depreciation on the extra capital required by the more costly electrical scheme. As the author gives no figures of present-day capital costs, I do not propose to discuss this, but I would point out that the capital required for the electric winding gear is only part of the cost. In addition to this the generating plant must be increased to supply the extra demand both of the electric winding gear and of the plant which was previously supplied by the mixed-pressure turbine. As the electric winding gear makes a big demand for its peak load, the additional capital required for the generating plant is a large amount and more than offsets the saving due to the fact that the mixed-pressure turbine would not be required. It will be well to note also that the auxiliaries for this larger generating plant would take considerably more power than those for the mixed-pressure turbine, and would work on a worse load factor. I think it is obvious, therefore, that in a number of cases the steam winding gear and the mixed-pressure turbine are undoubtedly the correct plant to install, and it would be necessary to generate at an extremely low coal consumption per unit in order to make electric winding the better proposition. Every case of this kind must be worked out on its merits, taking into consideration (1) the cost of generating or buying electricity, (2) the cost of coal used under the boilers for raising steam, and (3) the capital cost of each scheme. My present partner, Mr. Mountain, went very fully into this cost for the electric winder versus the steam winder in the paper which he read before the Institution in 1906, and showed that at that time there were few cases where the electric winder

was best, owing to the small value of the coal which was used for raising steam, and to the high capital cost of the electric plant. It was generally realized that the electric winder would require less coal to be burnt under the boilers for a given work than would a steam winder, but the value of the coal saved was so little that it was not sufficient to offset the extra interest and depreciation required on the costly electrical winder. Since that date conditions have altered considerably and there are more cases to-day where the electric winder may be the right equipment than when the paper was read, but on the other hand the developments of the mixed-pressure turbine is a factor tending to increase the number of cases where the steam winder is the better proposition. I do not wish it to be thought that either Mr. Mountain or myself is an opponent of electric winding—that is by no means the case—but we feel it is never of advantage to the industry to install plant which does not give the best commercial results, and consequently it is desirable to treat every case on its merits, taking into account the numerous factors which affect the financial result, the only one of interest to the mine owner. During the discussion with regard to the efficiency of compressed-air transmission, reference was made by several speakers to the loss which occurred in the underground distribution of this power. A short time ago I had to make some tests of the leakage of air at a colliery, and in this particular case I found that while about 4 000 cubic feet of free air was being supplied to the pit in question, of this amount 1 500 cubic feet of free air was escaping without doing any work. This is by no means an isolated instance and shows a leakage of about 37 per cent during times of heavy load. When the load was reduced, with the leakage still remaining constant, the loss increased to nearly 50 per cent. In Table 4 the author gives particulars of the power required to run a Ward-Leonard generator when driven by a synchronous motor as 80 kW, whereas if driven by an induction motor the light-load loss is 115 kW. I should like some further explanation of these figures as I do not understand how the induction motor could take so much more power than the synchronous motor to do the same work. Is there anything abnormal in the machine referred to ?

Mr. D. Weir: I am interested to note that the author questions the advisability of running ventilating fans at low speed during stop-days and at week-ends. If the advantages of such a procedure are indeed doubtful it would seem ill-advised to install variable-speed motors for fan drives when a constant-speed machine of much superior operating characteristics might be used. As the author suggests, the increase of fan speed as the mine develops can be arranged for very simply by altering the ratio of the drive. The author's statements as to the higher efficiency and better all-round operation of the salient-pole type of synchronous motor as compared with the synchronous induction—or auto-synchronous motor, as it is sometimes called—are welcome. So much attention has recently been drawn to the synchronous induction motor that engineers are apt to overlook the claims of the older and more robust type of synchronous motor with salient poles. The salient-pole machine suffers from the disadvantage of not being able to start up against a heavy torque, but in the cases of air compressors and other drives where high starting torque is not required there would appear to be no justification for using the synchronous induction motor when a more satisfactory machine of higher efficiency is available. Reference has been made to the use of salient-pole synchronous motors in America for driving colliery fans, the torque being reduced at starting by closing the air outlet. Baffling of the fan outlet has been used for varying the air volume, and it only seems necessary to carry this a step further to permit of the use of salient-pole machines for fan drives. It would be interesting to have the author's views on the feasibility of applying this scheme to mine-ventilating fans in this country. Provided inexpensive arrangements could be made for baffling the fan outlet, the scheme would appear to have much to recommend it. It is stated that a complete Ward-Leonard winder (presumably with direct-coupled motor) costs about 30 per cent more than a geared induction motor winder. My experience has been that this figure is nearer 75 per cent. Apart from the reduction gearing, the mechanical equipments for the two systems are practically identical. On the other hand the Ward-Leonard system requires roughly three machines of the full winder capacity, one being a very large low-speed motor, as against one moderately high-speed machine in the case of the induction motor winder. When the larger winder house and the high cost of the cable work are taken into account, the cost of the Ward-Leonard winder may easily approach twice that of the geared induction motor winder. It is somewhat surprising to learn that the balance rope is not looked on with favour in South Wales, in view of the increasing popularity of this device in other districts. In addition to the economy in energy consumption, there is a considerable saving in the initial cost of the drum if by using a balance rope a parallel drum can be used in place of the more costly and much heavier cylindro-conical drum. The author exhibited a lantern slide showing a "pot" type of liquid controller in which the customary arrangement of vertically moving electrodes is retained. All such arrangements suffer from the disadvantage of inefficient circulation of the electrolyte. The heated liquid in rising by convection from the region between the moving and fixed electrodes is baffled in its flow by the upper electrode. A considerable advance has been made in a recent design of "pot" controller in which the electrodes move approximately in a horizontal path, thereby permitting free circulation of the electrolyte by convection. Heaviness of operation is a further disadvantage of the orthodox design of controller, necessitating in some cases the use of an air engine to assist the driver. In the new design referred to, this defect is overcome by swinging the moving electrodes in pendulum fashion and balancing them with a spiral spring which avoids the objectionable inertia of balance weights.

Mr. Christopher Jones: I suggest that the title of the paper should be amended to read "Electrical Power Plant at the Colliery Pit Head," inasmuch as the author does not refer to the use and application of

electricity *in the mine*. I personally should have welcomed some description of the plant used underground, together with the system or the troubles (if any) experienced on such a very large colliery undertaking. The author's remarks regarding fuel and water conditions are very much to the point and I am in agreement with him. He refers to the question of the improvement of power factor. This subject was considered by my company about 12 years ago when it was decided to install static condensers on the low-tension system at surface and underground substations. These have justified their installation from every point of view. In another instance when the question of conversion of a steam-driven ventilating fan to electrical drive came up for consideration, it was decided to install an induction synchronous motor drive direct coupled to the fan. This has been in continuous use for about 4 years without a moment's trouble. The author refers to speed reductions of ventilation fans at week-ends or stop-days which necessitate variable-speed motors or other mechanical speed-reducing devices, and his jockey pulley device is very interesting. I should like to ask him if he has had any experience with the Williams-Janney variable-speed gear and if he has considered such gear in connection with his undertaking for winding, fan or haulage drives. I agree with him that speed reduction at week-ends, etc., is a questionable economy, bearing in mind also the colliery manager's responsibility as to safety of the mine, and I doubt whether the mining regulations permit of such speed reductions. My own colliery manager confirms the author's views that it is safer to maintain full volume of air at all times, and this practice is in force. Mention is made of the unsatisfactory method of starting up squirrel-cage motors by means of auto-transformers. In this connection I would say that in my own case motors up to 70 b.h.p. only are allowed. These are started up by auto-transformers and no trouble has been experienced. The size of this type of motor is also governed by the capacity of the generating station and, in the case of bulk supply from an outside source, by the rules of the supply undertaking; these are in some cases very stringent in regard to the use of squirrel-cage motors. On page 522 the author states that the four most important loads are pumping, ventilating, winding, and air compressing. I presume that the author regards this as being applicable to his own undertaking, otherwise I disagree with him. At the collieries under my charge electricity is used on the surface for ventilating, haulage, pumping, screening and other works drives, *but no winding*. For underground purposes electricity is used for coal-cutting, pumping, haulage, auxiliary winding gear, compressor drives, other than conveyers, rock-head drills, punchers, and small haulage gears up to 10 h.p. which are compressed-air driven, electrically driven compressors being installed inbye. It would be of interest to hear the author's views regarding inbye compressors. The units generated at the colliery station for all power purposes during drawing hours average 3 per ton of coal raised, 70 per cent of the coal drawn being got by electrically driven long wall and arc wall coal-cutters. On page 536 the author refers to the advantage of the use of electricity in that the consumption of every machine or group of machines can be continuously recorded and any waste checked, the electrical plant retaining high efficiency without the constant adjustment and renewals necessary in other machines. Apparently here again the author refers to pit-head drives, as a large number of compressed-air machines must be used when analysing the curves shown. In view of the author's admission in regard to the advantages of electricity, will he say why compressed air is used on such a large scale and how he obtains the best results from such machines? I cannot understand his statement that the principal effect of electrification is to reduce the amount of unskilled labour employed at the pit-head, and I should be glad if he would amplify his remarks on this point.

Mr. G. M. Harvey: In the summary, the author states that the object of the paper is to show that the mining electrical engineering industry cannot rightly be charged with employing wasteful and unscientific methods, and the paper shows what high efficiencies can be obtained by means of the latest developments in electrical machinery scientifically applied to mining conditions. I would ask, however, whether there is not too great a tendency to strain after the last 1 per cent of efficiency, possibly at the expense of reliability, which is of greater importance in colliery working from the point of view of the management. A stoppage of one hour on the main haulage supplying a shaft from which, say, 2 000 tons of coal are being wound per shift, will mean a loss in revenue to the company of £300 or more, and will counterbalance several decimal points of efficiency in the motor. The author refers to the practice of washing low-grade fuel, and states that this should be done if the ash content exceeds 10 per cent. It would be interesting to know whether he has proved this practice to be economical, as it would appear that the cost of washing would more than outweigh the extra efficiency gained. It is common practice to burn, with ordinary hand-firing arrangements in Lancashire boilers, low-grade fuel having an ash content of up to 30 per cent. On page 522 the author states that auto-transformers are unsatisfactory for starting large squirrel-cage motors. Has he had any experience of the type of auto-transformer starter in which successive tapping voltages are applied to the motor during starting, thus gradually increasing the applied voltage by a number of stages? Once the difficulty of changing from step to step without open-circuiting or short-circuiting the transformer windings has been obviated, I believe that these starters give satisfactory service up to about 200 h.p. at least. The statement on page 524 with regard to the efficiency of transmission of compressed air is rather startling, and I think that the author might have emphasized the fact that this applies to surface transmission only. For transmission below ground, along shifting roadways, with bends every few yards and the ever-present possibility of damage from the collier's pick, transmission by compressed air cannot hope to compete with the electric transmission of energy. It would have been useful if the author had carried his comparison of compressed air and electric transmission somewhat further, and given the relative efficiencies of the three systems in practical

use, viz. (*a*) steam-driven compressors on the surface and air engines at the coal face, (*b*) electric generators on the surface and electric motors at the coal face, and (*c*) electric generators on the surface, electrically-driven compressors at suitable points below ground, and air engines at the coal face. The efficiencies of these systems are roughly as follows: (*a*) 25 per cent, (*b*) 60 per cent and (*c*) 15 per cent. The very large proportion of power taken by the compressing plants in the colliery referred to in the paper is, I think, an admission that we have not yet arrived at complete safety from shock and explosion in the use of electricity in an explosive atmosphere. In South Wales generally, one finds the electric cables terminating at points a few hundred yards inbye from the shaft bottom, whereas in more favoured districts, such as the Midlands, where we have not to deal with large quantities of explosive gases, the electrical installation extends to the coal face, and compressed air is used solely for percussive rock drills. The portion of the paper dealing with electric winders contains a very large amount of information, and goes to prove—if proof were needed—the intricate nature of the problems with which the mining electrical engineer has to deal, and the folly of attempting to handle such problems without a very full knowledge of mining conditions. It would be instructive if Table 6 could be completed by filling in the blank spaces in the last three columns, utilizing the pounds of coal burnt per unit generated by the electrical plant. Without these figures the comparison is incomplete.

Mr. H. Jack: The paper is of great value for the comparative data it gives based on actual tests and costs. I think that the author has proved the great advantage of running a group of collieries by means of a modern high-pressure steam-turbine-driven electric power station and the general use of electric motors. The consideration, then, of the best type of electric motor for each duty is important. I note that the author is not in favour of using the squirrel-cage type of motor for driving centrifugal pumps where the horse-power exceeds 150. This is contrary to the experience of some engineers in large mines abroad. I consider that the squirrel-cage motor, properly designed and constructed, is the most robust type of electrical machine, and that with substantially built auto-transformer or star-delta starters, squirrel-cage motors up to at least 1 500 h.p. could be used for driving centrifugal pumps and would give maximum reliability. The author was one of the first in this country to realize the great advantage of installing synchronous motors, both of the salient-pole type and the cylindrical-rotor type. At the same time he has wisely only installed motors of the synchronous type, where the output of the motor was of sufficient magnitude to make a substantial improvement in the power factor of the system. The type of synchronous motor shown in Fig. 2 is interesting, but from a manufacturing point of view it tends to be costly. One cannot use for its manufacture the developed pole dies of the salient-pole squirrel-cage type of synchronous motor, or the developed rotor dies of the induction motor. The synchronous induction motor with cylindrical rotor can be made with the dies developed for the ordinary induction motor. For this reason I do not think that the salient-pole motor with slip-ring type winding in the pole face is likely to be generally adopted by manufacturers. Where a starting torque of full load or greater is required, or where it is necessary to pull into synchronism against a torque of full load or greater, the cylindrical-rotor type of synchronous induction motor is being generally adopted. It is the cheapest type of synchronous machine for heavy starting duty, but its efficiency is at least 2½ per cent lower than that of the salient-pole synchronous motor. As regards the Lenix belt drive adopted by the author for driving fans, I should like to know the maximum horse-powers and speeds for which this type of drive could be used and what is the approximate life of a belt. Although for a considerable number of years the salient-pole synchronous motor has been adopted in the United States for practically all air and ammonia compressor drives, the extent of its use and success is not yet realized in this country. For starting duties up to at least half full-load torque, and where unity or leading power factor is required, the salient-pole synchronous motor is the ideal machine. As regards the method of starting I think that the best form of starting apparatus is on the lines of the Korndorfer arrangement described in the paper. With such a method the supply to the motor is never broken during the starting period. I hardly think that it is necessary to have all the 6 steps given on page 525. There is no apparent advantage in starting with the auto-transformer neutral open. The real advantage in being able to open the neutral of the auto-transformer is that one can pass from the tap connection to a choke-coil connection; on short-circuiting the choke-coil connection the motor gets the full line voltage. This avoids any sudden rush or kick of current such as is obtained if the tap connection from the motor is broken and the full line voltage then switched on to the motor. Further, I think that it is better, wherever possible, to synchronize the motor, i.e. close the field switch, while the motor is still running on the tap voltage. The author considers the characteristics of the induction motor in dealing with the control of a.c. winders. I think that the late Dr. Steinmetz was actually the pioneer in developing fully the characteristics of the induction motor. In Fig. 7 the author gives the well-known speed/torque curves of the induction motor. When considering the control of an a.c. winder motor the value of the curves would have been enhanced if the author had extended them to include regenerative working and had also given curves with greater external resistance. Curves showing the stator and rotor currents throughout the range of speed and for the various values of rotor resistance would also be of assistance in considering the control. His statement that too high or too low a resistance results in a reduction of the reverse-current braking effect at full speed is only correct where the resistance inserted is such as to give maximum braking torque at full speed. A further increase or decrease of this resistance would then lower the torque. This is a contingency that would practically never arise, as one would always have sufficient external resistance to keep the torque below its maximum value. With the external resistance

values corresponding to the curves of Fig. 7 the stator currents on reverse-current braking would all be approximately equal to short-circuit current, and the motor should not be run at such high values of current. If the motor is running with the proper external resistance value to give a braking torque of less than maximum torque, then to obtain an increased braking torque at full speed the amount of external resistance should be reduced.

[The author's reply to this discussion will be found on page 563.]

East Midland Sub-Centre, at Nottingham, 24 March, 1925.

Mr. L. G. F. Routledge: Table 1 is interesting in that it should dispel any illusions in the minds of those who still place their faith in gas engines owing to their high thermodynamic efficiency. There is, I believe, a 7 500-kW gas engine now being installed at works not far from this Centre, and the results of its working will be awaited with great interest. I should like to ask the author what are the various percentages for interest, depreciation, etc., which he allows under the head of capital charges in line 5 of Table 1. Questions of economical fuel consumption have not yet been seriously tackled in the Midlands. Most of the collieries have hand-fired Lancashire boilers, but some of them are now seriously going into the question and some results should be available for comparison in the course of the next year or two. On page 522 the author mentions power factor improvement and briefly dismisses the static condenser. It may be of interest here to state what has been done in the way of power factor improvement at a group of collieries with which we are connected. The author's conditions are more or less peculiar to South Wales, and the centres of gravity of his electrical load are, generally speaking, on the surface at the collieries. In this district electricity is taken to the coal face both for machine cutting and conveying, and the electrical centre of gravity usually lies somewhere between the pit bottom and the coal face. It is obvious that synchronous motors of small size cannot be introduced into the mine, and it is here that the static condenser shows to advantage. Table G gives some particulars of static condensers installed at this group.

Table G.

Capacity of static condenser	Date installed	Type	Cost of repairs and maintenance per annum
kVA			£
81	Oct. 1913	Old original type in 50 μF units	8
115	Feb. 1917	Old original type in 50 μF units	3
56	April 1919	Tank type	Nil
95	April 1919	Tank type	Nil
65	Oct. 1924	Tank type	Nil

We dispense with switchgear where possible and connect direct to the stator circuits of induction motors. Two of the above are connected to the stator circuits of small motors driving ventilating fans; the others are inbye. When the 115-kVA condenser was installed about three miles from the generating plant, while the load remained steady the weekly consumption of units was reduced by 840. This showed a saving of 17 per cent on its capital cost, taking into account only the costs of coal and water ruling at the time of its installation. At this group of collieries we installed in 1914 a salient-pole motor to drive a screening plant. This motor released three induction motors for other jobs and enabled an increase in transformer capacity to be avoided. It seems rather an extraordinary drive for a synchronous motor, but it was the only one available and something had to be done at the time. A synchronous induction motor of moderate size drives a fan installed in 1920. Mr. Weir, in reading the paper on behalf of the author, showed some interesting diagrams of fan drives by salient-pole motors in America and mentioned a starting torque of 50 per cent of full-load torque. I should like to ask how this is done, and what is the starting current. It is difficult under existing conditions in this country to get a starting torque of 30 per cent of full-load torque with reasonable starting current. I am afraid also that colliery managers would not agree to shut off the fan drifts while starting the fan. Some figures which we have obtained for motors to drive a 3 000 cubic-feet-per-min. air compressor at a synchronous speed of 250 r.p.m. may be of interest as they do not bear out the author's statement as to the immense superiority of the salient-pole motor. The figures given in Table H were obtained over 12 months ago. The

Table H.

	Induction motor	Synchronous induction motor	Salient-pole motor
Capital cost ..	100	118	132
Power factor ..	—	0·85 lead	0·85 lead
Full-load efficiency	93 %	92·2 %	92·5 %

Table J.

	Induction motor	Synchronous induction motor	Salient-pole motor		
Capital cost	100	130	135	142	150
Power factor	0·82	unity	unity	unity	unity
Full-load efficiency	94	93·8	93	92·5	94

figures of capital cost include main switch and starter and an allowance for saving on the compressor bed in the case of the salient-pole motor. The figures of efficiency are not strictly comparable with the author's as they are at 0·85 leading power factor. Some figures recently obtained in connection with a second 3 000-cubic-feet-per-min. air compressor at the same speed are given in Table J. The above figures are from various makers. The figures in Table K, however, are

TABLE K.

	Induction motor	Synchronous induction motor	Salient-pole motor
Capital cost ..	100	114	132
Power factor ..	0·82	unity	unity
Full-load efficiency	92·5	93·8	94

from the same maker. Taking the cost of the induction motor in Table J as 100, the induction motor in Table K costs 108. The figures in Table L are also

TABLE L.

	Induction motor	Salient-pole motor
Capital cost	100	98·5
Full-load efficiency ..	92·5	93
Full-load power factor ..	0·8	unity

from one maker. This is the most expensive induction motor offered and the cheapest salient-pole motor.

In connection with Part 2 of the paper the following figures may be of interest as showing how conditions vary in different parts of the country. At a group of collieries near Nottingham where the whole of the plant with the exception of winders and locomotives has been electrified, the figures are as follows :—

	Units per ton raised
Ventilating fans	2·72
Pumping	0·21
General pit use	4·15
Compressed air	—
	7·08

If the winders were electrified the consumption would be approximately 2·5 units per ton raised, making a total of 9·58 units per ton raised. These are very old pits with thin seams a long way out. The average depth from the surface is 300 yards and the coal raised per pit is about 1 000 tons per 7-hour shift. The figure 4·15 includes screening, washing, workshops, coal-cutters, haulages, and a few face and gate conveyers. At another pit in South Yorkshire drawing about 2 200 tons per 7-hour shift from a depth of 630 yards the figures are :—

Winders	Steam
Fans	Steam
Compressed air	2·1 units per ton raised
Inbye haulages	1·1 units per ton raised
Pumping	0·1 unit per ton raised
Washing	0·8 unit per ton raised
Screens, shops and other uses on surface ..	2·4 units per ton raised
	6·5

If the winders and fans were electrified the total would be about 13 units per ton raised. I should like to ask the author if he has any motors with Boucherot rotors, and, if so, what are the starting torques and currents obtained with them. I agree with him that it is very questionable economy to install variable-speed or cascade motors for fan drives. I have known one or two cases where two-speed motors have been installed and only run on top speed, due partly to the desire to maintain the full volume of air at week-ends and partly to the difficulty of finding suitable men to change the speed of the motor in question. The examples of the Lenix drive shown on the lantern slide were extremely interesting, as indicating what can be done in economizing space and making what is apparently a very simple and reliable arrangement. What does the author consider to be the maximum horse-power that can be transmitted by this method? I quite agree with the author's remarks on the economy of the electric winder, and under suitable conditions where the colliery only runs one 7-hour shift the steam winder with mixed-pressure turbine has no case against the electric winder, although of course the Ward-Leonard equipment is more favourable the longer the coal-turning period. As a matter of fact there are cases in this district with steam winders already existing where it is false economy to install mixed-pressure turbines as against high-pressure sets. In considering electric winding each case must be judged on its merits. Where there is an unlimited power supply without risk of excessive voltage-drop, Stjernberg's coefficient is a very useful way of analysing the problem, but this cannot apply to those collieries with small generating plants and transmission systems where new generating sets and increased capacity of transmission lines would have to be installed to supply a.c. winders. The value of the paper would have been enhanced had a table of rope and drum diameters and life of ropes been included. Mr. Weir mentioned several cases of drums from 12 to 13 ft. dia. on the small diameter with ropes of 2 inches dia. and larger. What type of ropes are these and what life is obtained with them? The author mentions fully automatic control with the Ward-Leonard system, but I should like to ask whether he has tried fully automatic control. It was pointed out that a way of complying with the regulations and keeping all the plant in one engine room is to keep the winding engine man in a cabinet. Why not in the case of Ward-Leonard control move him to the pit bank where he could have absolute control over the cage and save the time of signalling

between pit bank and engine house? A better alternative in those cases where electro-pneumatic decking is in use would be by an extension of the decking plant control lever to make him operate both the decking plant and the hoist. Has the author had any experience, where automatic keps are in use, of the keps being pulled away when there is a certain amount of slack rope above the cage? If so, how does he guard against this contingency? With the Ward-Leonard control and semi-automatic cam gear, does an engine man ever pull his lever back and stop before the ascending cage has reached the keps? If this happens with a cylindro-conical drum, will the slight movement of the control lever enable the motors to exert sufficient torque to raise the loaded cage on to the keps, and, if not, how is this difficulty overcome without waste of time? Mr. Weir explained that there is a spring attachment to the control lever which enables it to move sufficiently to give the motors creeping speed, but this does not explain whether that movement enables the motors to exert sufficient torque to lift the loaded cage on the large diameter of the drum. On page 529 the author compares the efficiency of the direct-coupled low-speed d.c. motors with the higher-speed geared motors on the Harworth colliery winder. Taking the capital cost of the whole equipment, including flywheel set, exciter, control board and complete winder (excluding foundations, buildings and cables) as 100, the cost with low-speed direct-coupled motors would have been 123, or, taking the mechanical and electrical parts of winder only as 100, the equipment with low-speed motors would have cost 142. Apart from considerations of reliability, maintenance costs, etc., the efficiency of the motors and gears on the Harworth winder could drop to 75 per cent before the direct-coupled motors would show a saving on the score of efficiency only, so that there is here a large margin for repairs and maintenance. It may be of interest to compare the corresponding steam consumption (running light) of the flywheel set given at the top of page 530, with the Harworth flywheel set. This set when running light takes 3 650 lb. per hour (including allowance for condensing plant) with 150 lb. per sq. in. steam pressure, 100 degs. F. superheat and 28 in. vacuum (actual figures, bar. 30 in.). The flywheel weighs 22 tons, is 12 ft. in diameter, has two 875-kW d.c. generators and eddy-current brake, gears, turbine, etc., and the stored energy at 750 r.p.m. is approximately 83 million ft.-lb. The estimated stored energy in the author's set at 500 r.p.m. is 55 million ft.-lb. Assuming 180 kW input to induction motor, 10 per cent loss on transmission, 96 per cent generator efficiency, and similar steam conditions, would give 3 000 lb. of steam per hour. This is 26 per cent in favour of the steam-turbine-driven flywheel set. This could, of course, be considerably improved by increasing the pressure and superheat, but owing to there being boilers already in existence the plant was handicapped to that extent. This plant is not yet operating under anything like its full-load conditions, viz. 300 tons per hour from a depth of 940 yards, so that it is impossible yet to give any actual figures of results of working. The coal being raised at the present time is just under 400 tons in the 24 hours. The author's application of the synchronous motor to drive the Ward-Leonard equipment is extremely interesting and further information about his device for keeping a steady power factor on the motor during the large fluctuations of load would be welcome. With regard to Part 3 of the paper, I quite agree with the author that the stand-by losses are more considerable than they are usually thought to be. It would be interesting if the calorific values of the fuels were given. At the group of collieries previously mentioned where there are four winding engines exhausting to atmosphere and only a small proportion from two engines going to a mixed-pressure turbine, the fuel consumption remains steadily year by year in the region of 3·5 per cent of the coal raised, but this may be due to the fact that it may be of much higher calorific value than the 4·72 per cent mentioned in the paper, owing to the boilers being mostly hand-fired Lancashire boilers. The whole of this group of collieries is electrically driven from a central generating station at the central mine of the group. Only the winding engines are steam-driven. In conclusion I should like to ask the author why he has gone to so much trouble to reduce the starting peaks on his compressor motors when he has so many large a.c. winders on his system.

Mr. A. D. Phillips: I notice from Table 2 that a very large proportion of the energy used in the South Wales coalfields is apparently for compressor purposes, and I gather from Mr. Weir's remarks that this is accounted for by the fact that the colliery managers and engineers will not have electricity used at the coal face. In the Midlands I believe that there is very little compressed air used for this purpose and that electricity is generally favoured. I should therefore be interested to know whether the different policy adopted in South Wales is due to different conditions or whether it is dictated to some extent by prejudice. I gather from the paper that electric winding is fairly extensively used in South Wales and, from the figures given, this type of winder apparently shows a considerable improvement in efficiency over the steam winder. In the Midlands the practice is again the reverse, and I should like to have the author's views as to whether in this case this is due to prejudice on the part of the Midland colliery owners. From the figures put forward as to the efficiency of electric winders it seems to me that if these figures are correct any colliery owners who fail to adopt electric winding in connection with the new coalfield development in Nottinghamshire will find within the next 5 to 10 years that their equipment, although comparatively new, is entirely out of date.

[The author's reply to this discussion will be found on page 563.]

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 20 APRIL, 1925.

Mr. R. F. Bull: Referring to the author's opening remarks, I would say that in Lancashire also efforts have been made to achieve efficiency. In 1899, electrical energy was generated for lighting, haulage, coal-cutting, etc. In 1903, steam turbines driving three-phase alternators were installed, and in 1913 two sets of electric winders were ordered with Ward-Leonard-Ilgner control by the same colliery company. On page 522 the author refers to the pulverizing and burning of inferior coals. Can he give any figures comparing the cost of burning similar coals, not pulverized but hand-fired, in Lancashire boilers? Is the winder referred to in Table 2 an a.c. or a d.c. machine? At a Lancashire colliery, completely electrified except for one winding engine, the units per ton (not including the electric winders) were as follows:— Air compressors 12, fan 6, other plant (surface and underground) 7; total 25. This colliery is in its early development stages. At another colliery, completely electrified with the exception of its steam winding engines, the total units used vary from 8 to 10. The low figure is due to the very small amount of compressed air used. Does the author find any extra wear on the motor bearings with the Lenix drive, and has he experienced any trouble with the belt not gripping after it has been out of commission for some time? Referring to the two-speed motors, it would seem that three speeds are really necessary—the middle speed for ordinary running, low speed for week-ends (if required) and high speed in case more air is required in the mines due to a sudden outburst of gas. On page 524 the equivalent h.p. for 6 396 cub. ft. per min. at 75 lb. per sq. in. is given as 1 038. The comparison seems hardly fair to the reciprocating set unless the steam consumption of the turbo compressor is taken when it is developing 6 396 cub. ft. of free air per minute. Can the author say what is the running cost per 1 000 cub. ft. of air, comparing the turbo compressing plant, pipe line, etc., with electric transmission and reciprocating compressors? Fig. 4 shows typical load curves for a compressed-air plant and an electrical plant. The scale of loads is not given, but it appears that one or more 40 000 cub. ft. turbo compressors have to be started up and shut down before and after the day shift respectively. I should imagine that this is not very good practice for large turbines. The author refers to the automatic air-controlled inlet valve on the vertical compressors, which is closed when the pressure exceeds a predetermined value and compression ceases, to commence again when the pressure falls by a few pounds per square inch. There is another type of control gear for electrically driven compressors, consisting of rotary unloading valves on the suction sides of the high-pressure and low-pressure cylinders. These valves can be adjusted to operate one after the other so that the load can be taken off and put on gradually, to reduce shocks on the compressors and sudden variations on the power station. It would be interesting to know what air meters the author uses, also if he has had any trouble with his pipe line due to water, expansion, or contraction. There is a great demand for air meters at a reasonable price for placing in branch mains to check the flow of air to various districts. How does the winding-motor control compare with the synchronous-motor-driven converter set against the flywheel set from the point of view of accelerating and retarding quickly? Referring to Table 1, I should be glad if the author would state whether the installation working with steam at 350 lb. per sq. in. pressure and 700° F. results in any considerable saving.

Mr. E. W. Ashby: Curves are given in the paper comparing the efficiency of motors of geared and direct-driven winders. The system dealt with in the paper will have a high power factor owing to the liberal use of synchronous machines, but I think it would be of interest to those who use ordinary induction motors to compare power factor for high-speed and low-speed winding motors. Regarding Mr. Bull's remark about the cascade motor, I have handled inquiries for these over a period of six years, and three-speed motors are often asked for. Taking a single-wound cascade motor having two speeds of 500 and 333 r.p.m. (50 periods), the third speed with this winding would be 1 000 r.p.m. The top speed would thus be too high to meet the conditions set out by Mr. Bull, and to obtain a third speed of 600 r.p.m. a second stator winding is necessary. This increases the cost by about 20 per cent over that of a two-speed machine. The additional speed is well worth the extra outlay, but in the majority of cases the colliery engineer decides on the two-speed motor.

Mr. H. Pryce-Jones: I should like to ask whether the Stubbs-Perry scheme, the details of which Mr. Perry has given, can be used as a straight a.c. equipment. The drop in speed necessitated by the giving up of the kinetic energy of the flywheel would of course result in a frequency variation, which in turn would have an adverse effect upon the electrical efficiency of the generators and winder motors. If an a.c. equipment has been utilized in this arrangement, how does its overall efficiency compare with that of a Stubbs-Perry scheme operated upon the d.c. Ward-Leonard principle?

Mr. T. Hodge: The paper is in my opinion rather in the nature of a treatise on "Electricity *at* Mines," than "*in* Mines," and although the author gives some very interesting figures in regard to the production of power and the methods of its application, I am sorry that the transmission of it has not been touched upon more with reference to underground purposes. Has the old trouble of the cores of the pit-shaft cables being squashed together by the clamps holding the cable, and the consequent short-circuits, been entirely overcome? What progress has been made along the main roads to ensure that cables are impervious to damage in case of falls of roof, or at such times as the tubs or wagons threaten to bring all the props along with them on their journey? In view of the reports of fatal accidents, would it not be possible or economical in the case of distributors to transform down to a safe voltage within a reasonable distance from the coal-

cutters? With regard to the motor on the coal-cutter, and its trailing cable, does the author consider that it will ever be safe in the light of recent developments to use it in any working place where safety lamps are necessary? It is pleasing to see what strides have been made in the use of electricity for winding, but I fear that there will not be a large field for electric winders in England in the future, mainly on account of capital cost and the depleted state of the coalfields. I was surprised to read on page 524 that the transmission losses with electric power and compressed air are so nearly equal. With regard to the latter part of the paper dealing with the amount of unskilled labour, I do not see that electrification can affect much economy, since the few skilled labourers require a higher rate of pay. In addition, they might at times be more difficult to manage than some of the unskilled. Is not the principal effect of electrification a higher plant efficiency?

Mr. C. Rettie: I do not quite understand the system proposed for small collieries and should like some explanation on this point. For instance, I was always under the impression that the Ward-Leonard, Ilgner, or cascade system was far superior to any other, no matter what size the colliery happened to be. What, for instance, becomes of the peak loads in the system proposed by the author? With regard to the economies gained by the use of electricity in mines, I have always laid down in other directions that economy is not always the deciding factor, but rather the ability to do things more safely and better. With regard to mine signalling, as the driver does not see what is going on in the shaft he depends entirely on reliable signalling apparatus, and this, in addition to providing safety, must affect the economical working of the mine.

Mr. E. M. Hollingsworth: Unfortunately, for financial and other reasons, the colliery companies in this area have not seen their way to adopt the progressive policy of the South Wales owners, and, as in the case of the Powell Duffryn Co., with the excellent results given in the final part of the paper. The advantages of electrical working generally in the mines are well known, but outside the South Wales area there are very few cases where electric winding has been adopted. That part of the paper dealing with winding is therefore of great interest, particularly the comparison of the merits of the a.c. and d.c. systems, and the control apparatus. The author has not hesitated to apply synchronous motors to drives for which a few years ago such motors would not have been considered suitable, and his experience goes to show that the synchronous motor is satisfactory and, of course, is of great value as regards power factor improvement. Is any great progress being made in the direction of the replacement of compressed air by electricity at the coal face, also what recent improvements have been made in the direction of reducing risk with electrical machines in gassy mines?

The Author's Reply to the Discussions before The Institution and at Manchester, Newcastle, Birmingham, Nottingham, and Liverpool.

Major E. I. David (*in reply*): I propose to deal with the various points raised, under separate headings.

Boiler fuel.—Mr. Sparks, Mr. Burgess and others refer to the various fuels burnt under colliery boilers. I agree that it does not pay to burn dirt; but coke breeze, washery slurry, froth flotation slurry and other difficult but clean fuels can be and are being burnt by blanketing or mixing with other fuels. Mr. Burgess also refers to burning coke breeze alone, and other low volatile fuels with thick fires, but he obtained only 55–60 per cent efficiency and outputs of 60–67 per cent of the boiler rating. I would point out that by the blanketing method average efficiencies of 82 and 100 per cent boiler outputs with 12–13 per cent CO_2 are being continuously obtained. This replies also to Mr. Harvey's question in regard to coal-washing. With 30 per cent ash in hand-fired boilers an efficiency of 55–60 per cent would be a good result. Coal-washing is not expensive—it is the loss of weight in the removed dirt that makes the principal difference in the cost of washed and unwashed coal. If people would buy on calorific value and burning properties, all small coals would be washed and railway carriage on ashes saved.

Mr. Mountain's long experience in mining electrical engineering makes his extensive contribution to the discussion of the greatest value. I agree with all his remarks on boilers. The old fallacy of the reserve steam capacity of Lancashire boilers still deludes people into installing them where steam winders are used. The largest steam winder at present installed takes 800 lb. for one wind, and this weight of steam would hardly make a visible movement in the water gauges in the necessary bank of water-tube boilers. In comparing gas engines and gas-fired boilers, Mr. Mountain takes a boiler efficiency of 70 per cent only, whereas I take 82–85 per cent; otherwise our results are identical. For my comparative figures I refer him to Table 1. His tables giving generating costs under various conditions are interesting, but the size of units taken is very small compared with the power equipment of a modern group of collieries. The capital costs in Table A are very high, also the labour cost; gas at 6d. per 1 000 cubic ft., calorific value 450 B.Th.U. per cub. ft., is equivalent to coal of 12 500 B.Th.U. per lb. at 31s. per ton and is too high. A charge of 4d. would be more reasonable. The coal costs and labour charges in Tables B and C are again high owing to the small plant. Table D is based upon the assumption that low-pressure steam costs nothing, but I cannot agree to this assumption. I consider that the cost of steam to the high-pressure engine and the low-pressure turbine should be charged in proportion to the heat-drops in the two machines. This is normally 50 : 50. On this basis, taking the low-pressure steam consumptions of the mixed-pressure turbine as double that of the high-pressure turbine, the cost for steam would be the same for each machine. This would make the costs per unit of the mixed-pressure machine practically the same as those of the high-pressure

machine in Table B. The condition that the available low-pressure steam exactly corresponds to the load during working and night shifts is most unusual, and high-pressure steam is required to bridge gaps in the low-pressure steam supply. Mixed-pressure turbines are normally extravagant on high-pressure steam and, in my experience, units generated by mixed-pressure turbines cost more than those produced by high-pressure turbo units. Further, double quantities of steam require double the amount of condensing water, and this is usually a further objection to mixed-pressure turbines. Pages 534 and 535 and two of the lantern slides exhibited show that there are other losses in connection with steam-winder mixed-pressure turbine equipments and that where electric power is available at a moderate cost per unit, or can be produced for coal consumptions of less than 3½ lb. per unit, the complete electrification of winders, fans and all other machines is justified.

Mr. Routledge's remarks on the large gas engines (presumable for blast-furnace gas) and coal economy in the Midlands are interesting. In Table 1 interest is taken at 6 per cent, amortization at 15 years for plant, and 25 years for buildings, etc.

In reply to Mr. Bull, I have no figures for hand-fired Lancashire boilers but have burned coals down to 9 per cent volatile in pulverized-fuel equipments. The efficiencies were no better than those obtained by the sandwich method on a chain-grate stoker with balanced draught. I would refer Mr. Bull to the last paragraph on page 521 for a reply to his query in regard to high-pressure and high-temperature steam.

Switchgear.—Mr. Burgess and Capt. Mackintosh agree with my appreciation of compound-filled switchgear. I find, as they do, that it is just as easy to change a compound-filled transformer chamber as a set of current transformers in a cubicle, and in all other directions it is equally flexible. I strongly recommend its use in screening plant, owing to its immunity from dust troubles.

Winder switchgear.—Dr. Garrard, Messrs. Sparks, Mountain, Perry, Weir, Maclean and others are evidently in agreement with me in regard to winder reversing-switches. After one million operations of the compressed-air-operated air-break type, the contacts show only 7/1000 in. of wear, and the maintenance cost is nil.

In reply to Mr. Lloyd, my figure of £150 per annum refers to a number of oil-immersed reversing-switches, both hand- and contactor-operated, and is an average figure. Oil renewals alone on one contactor switch amounted to £10 per month. The air-break air-operated contactor is actually cheaper than an oil-immersed type of equal capacity, but takes up slightly more room.

In reply to Mr. Burgess, my experience of oil-immersed contactors covers the four principal makers and extends over 13 years. On a winder which makes or breaks a magnetizing current of 100 to 120 amperes at 3 300 volts 6 to 8 times a minute for 8 hours, the contactor must be examined daily and the oil changed at least once in four weeks. There is no difficulty in housing air-break contactors in the basement of an engine house in a suitable stone cell with interlocked doors. Air-break contactors are used on trains where the space is far more confined.

Power factor correction.—Mr. Routledge accuses me of dismissing the static condenser as hardly worth consideration. Far from it. I refer on page 522 to my contribution to the discussion on Kapp's paper where I recommend the static condenser for use in the very conditions he specifies and give an instance of the economies effected by the installation of a 235-kVA 3 300-volt three-phase 50-cycle condenser. His figures confirm mine.

Power utilization.—Messrs. Maclean, Routledge and Bull give comparative figures for the consumption of electricity per ton in various districts. I have collected these into Table M and have included those given in Tables 2 and 7.

TABLE M.

Units per ton raised.

District	Winder	Fan	Pit use	Pumping	Compressed air	Total
Table 2	4	3	1·5	3·5	20	32
Table 7	3·91	4	3·71	—	15·1	26·72
No. 1	3·88	3·04	1·71	1·01	16·57	26·21
No. 2	8·08	3·70	0·64	10·01	27·50	49·93
North-East Coast—						
No. 1	2·23	1·27	3·66	1·00	—	8·16
No. 2	1·32	2·07	2·88	1·41	—	7·68
No. 3	1·99	2·47	1·33	1·11	—	6·9
No. 4	3·21	4·27	8·88	5·14	—	21·5
Midlands and Yorkshire ..	—	2·72	4·15	0·21	—	7·08
Lancashire	—	6·0	7·0	—	12·0	25·0

In the case of the North-East Coast, Nos. 1, 2 and 4, the units for pit use include the power used for compressed-air production. General pit use in the South Wales table does not include a washery, coal-cutters or conveyers. The Midlands appear to be fortunate in having a very low pumping load. No. 1 colliery is an old one in which a portion of the conveying and cutting

is done by compressed air. The depth is moderate and there are a number of horses underground. No. 2 colliery is a deep colliery in which the whole of the output is conveyed by compressed-air-driven conveyers and there are no horses underground. Mr. Routledge's figures form a very interesting comparison with Tables 2 and 7. Ventilation is naturally a heavier load in the gassy South Wales seams in the proportion given, i.e. 4 to 2·72 units. The figure of 4·75 per cent of coal consumption in Table 5 includes steam engines, fan engines, compressors and mixed-pressure turbine. The figure for winders and mixed-pressure turbine alone is 2·48 per cent, whilst for winders, mixed-pressure turbine and fan engine it is 3·15 per cent, which is probably better than his figure of 3·5 per cent, owing to the higher boiler efficiency. The calorific value of the fuel varies from 12 000 to 13 000 B.Th.U. per lb.

In reply to Mr. Bull, the winder in Table 2 is Ward-Leonard controlled, as this is a necessity for an output of 300 tons per hour from a depth of 700 yards.

Pumping and pump motors.—In reply to Mr. Routledge, I have a number of motors running with Boucherot rotors up to 150 h.p. at 1 500 r.p.m. They take about $1\frac{1}{2}$ times full-load current to start against normal turbine pump torque and run up to speed very smoothly.

Fans.—In reply to Mr. Juhlin, I suggest the possibility of the use of a clutch for fans or compressors but do not advocate its use. I agree that the synchronous induction motor is the most suitable for fan drives and have installed over 20 in the last two years.

Mr. Jones refers to Williams-Janney gear. I think it is quite unnecessary for fan drives, as all requirements are met by single-speed or two-speed motors with 15–20 per cent higher efficiency, but there is a limited field for its use in haulages and small winders.

Mr. Bull requires a three-speed fan motor. This would mean some sacrifice in efficiency and reliability.

In reply to Mr. Routledge, the figures for American fans starting with drift doors closed are only of use to show what can be done by co-operation, but in this country such tests are improbable for the reason he states.

Fans; Lenix drive.—In reply to Mr. Mountain, the Lenix drive is more efficient than a rope drive, takes half the space and has a range of speed up to 12/1. The maximum power transmitted by the Lenix drives shown in the lantern slides is 600 h.p. at 120 r.p.m. at the fan shaft.

Fans; special salient-pole high-starting-torque motors.—Mr. Jack and Mr. Mann are correct. The type of motor in Fig. 2 is expensive and unnecessary. All requirements can be met by the induction or salient-pole types. I agree that it is better to synchronize (i.e. close the field switch) on salient-pole machines on the tap voltage, as this reduces the current carried and broken by the switch contacts to a very low value (at unity power factor) with correspondingly increased life. If Mr. Mann will examine Fig. 1 he will find that the horse-power is given clearly in the diagram on the bottom line. This diagram refers to a synchronous induction motor. The voltage of excitation of the salient-pole motors is 110 volts.

Fans; comparison of steam and electric drive.—Mr. Mountain's figures for steam-driven and electrically-driven fans can be compared directly with Table 8 of the paper, as the fans are identical in size. My figures are actual results of several years' operation. He does not debit the electrical equipment with any capital charges. In Table 8 the actual costs for motor starter and Lenix drive were £1 400, giving a yearly charge of £175. No spare boiler plant is allowed in his steam equipment. This would add considerably to his capital costs. The actual steam equipment in Table 8 consisted of two Babcock boilers and a low-speed drop-valve rope-drive engine. The coal consumption was 6 500 tons per annum. At Mr. Mountain's figure of 12s. per ton, as taken in his power cost tables, this amounts to £3 900 per annum. Maintenance, capital and other charges amount to £1 600 per annum, making a total of £5 500 per annum. For the same quantity and water gauge the units consumed by the same fan electrically driven were 2 100 000 per annum. Deducting the capital charges for the electrical equipment, £175, from the total cost for the steam fan, £5 500, leaves a yearly charge of £5 325 for the electrical units, or a permissible charge of 0·6d. per unit.

A fan, being a 100 per cent load factor load, is very desirable, and, when added to the other electrical loads, has a great effect on the colliery load factor. Taking Mr. Mountain's own figures in Table B, a normal load factor for other loads at a colliery would be 30 per cent, excluding compressed air, or, in Table B, 2 600 000 units per annum. Adding the above fan load of 2 100 000 units gives 4 700 000 units, improving the colliery load factor to 53 per cent and reducing the unit cost from 0·653d. to 0·47d. Further, the fan drive is, as shown elsewhere, particularly suited for a synchronous motor or other power-factor-improving drive and, in my opinion, should be one of the first machines electrically driven.

Compressors and compressed-air transmission.—Mr. Sparks, Mr. Johnson and others refer to the efficiency figures given for compression and transmission of air for use underground and suggest that these figures are misleading. I assumed that it was general knowledge that compressed-air engines without interheating can only recover from 20 to 25 per cent, and with interheating 30 to 35 per cent, of the energy used in compressing the air. Therefore compressed air will only be used where it is inadvisable to use electricity. Progress in mining methods and improved ventilation will open up more places where electricity is permissible, and we must put up with the inefficient but otherwise satisfactory air engine while we make our air-compressing and transmission plant as efficient as possible.

In reply to Mr. Harvey, Mr. Wood and others, comparative efficiencies for compressed-air production and transmission were given to the pit-head only. At this point the equipment usually passes out of the hands of the electrical engineer. Leakages below ground are seldom less than 15 per cent and often more than 50 per cent of the total volume. Part of this is used for ventilation.

Mining electrical engineers are aware that with reasonable precautions and properly designed apparatus it is safe to use electrical machinery underground, but under the Coal Mines Act it must be shut down when gas is present, whereas compressed-air machinery can continue to operate and its exhaust

helps to purify the working place. Leakage underground is a bugbear, but careful attention to the total consumption of a colliery, combined with week-end pressure-drop tests, can keep the engineer informed of the extent of the leakage. I agree with Mr. Burgess as to the absolute necessity of care in maintenance, even when the most adequate apparatus is installed.

I do not agree with Mr. Johnson that it has long been appreciated that air transmission is more efficient than electrical transmission over short distances. Eminent mining and electrical engineers, including a number of contributors to this discussion, have been surprised at the efficiency achieved in compressed-air transmission.

Mr. Mountain appreciates what many other speakers have not done, viz. that compressed-air power is a necessity in certain places. The efficiency figures given on page 524 refer to a Bellis and Morcom compressor and I endorse Mr. Mountain's appreciation of these machines. Wear and tear of all parts of inbye compressors is excessive and they are not to be recommended. Further, their diversity factor cannot compare with that of surface or central-station machines. Mr. Mountain suggests that the makers should be consulted with regard to the type of unloading device to suit the motor. When this was done in 1919 they all required 100 per cent starting torque. The experiment referred to on page 523 was made as a result. Mr. Mountain overlooks the fact that salient-pole synchronous motors not only improve power factor but at unity power factor are at least 2 per cent more efficient at full load and 20–25 per cent more at light loads than induction motors. My remarks on fan drives apply equally to Mr. Mountain's figures for compressor drives.

In reply to Mr. Bull, the comparison of the two types of compressors is taken at full output in each case. The running cost of the electrically-driven sets is about 10 per cent higher than that of the steam turbo type and pipe line, owing to the higher efficiency and lower maintenance cost of the latter. No difficulties result from the practice of running one steam turbo-compressor for 7 hours per day. A number of other turbines have to be run during the working shift period only.

Both B.T.H. and Kent indicating and recording air meters have been in use for some years with satisfactory results. Siemens-Halske meters are also used; these have an electrical recording device. Water traps are used in low places on the air mains, and no trouble has been experienced due to water or expansion, though very few expansion joints are fitted.

In reply to Capt. Mackintosh, the figures on page 524 show the superior efficiency of steam-driven turbo-compressors of large size over electrically-driven sets, but the group of collieries cited have over 12 000 h.p. of electrically-driven compressors (mostly with synchronous motors) for the very purpose which Capt. Mackintosh suggests, i.e. to balance the load between the electrical and air systems and to improve the power factor generally.

Mr. Simon suggests that if electric power were used instead of compressed air the average figure given in Table 2 would be reduced from 20 units to 6–7 units. I would go further and say 4–5 units.

Compressor drives.—Mr. Johnson and Mr. Juhlin doubt the comparative efficiencies given for salient-pole and induction type synchronous motors. The efficiencies are test-figures of two machines of the same horse-power and speed at unity power factor, each by the maker who most strongly advocates the competing type. They are directly coupled to compressors. The salient-pole machine has given no trouble, but the induction type machine has been shut down with various troubles for 25 per cent of its time. I do not agree that a difference of only ½ to 1 per cent is usual, and I would refer Mr. Johnson to my contribution to the discussion on Carr's and Kapp's papers referred to on page 522.

Mr. Routledge's figures for the relative costs and efficiencies of synchronous induction and salient-pole motors do not agree with mine, which are for larger lower-speed machines, necessitating a double winding on the induction-motor rotor. Corresponding figures of machines of the size he gives, obtained two years ago, were, at unity power factor :—

Induction motor	Synchronous induction motor	Salient-pole motor
92·5	93	94·5

Compressor drives; auto-starters.—Mr. Juhlin and Capt. Mackintosh appear to think that I am prejudiced against auto-starters. After several years' trouble with the starting apparatus on two 1 000-h.p. 1 500-r.p.m. squirrel-cage pump motors, these were altered to slip-ring machines and there has been very little further trouble. With regard to the 1 125-h.p. salient-pole machines, I would refer Mr. Juhlin to page 524 where it is specifically stated that the chief trouble lay in the auto-transformer. Three different makes have given trouble, so it is not confined to any specific design.

In reply to Mr. Routledge, no special effort has been made to reduce the starting peaks on compressor motors; the oscillographs were taken and other tests made with the object of eliminating breakdowns in the starting gear.

Mr. Harvey's suggestion of a number of stops for auto-transformers would not prevent the troubles on the smaller sizes, which are principally due to sheer abuse. For large machines the ideal starter would be an induction transformer with a short-circuiting switch.

Electric winders.—Mr. Horsley and Mr. Mann refer to automatic control. Two of the a.c. winders illustrated in the lantern slides have electrically-operated control of the type they refer to, but I prefer the well-tried Whitmore or profile mechanical device. Either of these gives continuous control of speed throughout the wind, and sensitive overspeed setting. In addition, I fit overwind switches in the headgear in case of failure of the speed-control drive, as in the recent Cwm Colliery accident. The brake application should be graduated during the high-speed portion of the wind, but instantaneous in case of overwind. I do not see any reason why future electric winding plants may not be fully automatic, combined with automatic decking under the control of one man in an enclosed cabin at the pit-head. I have not tried full automatic control on a Ward-Leonard winder. The spring connection in the cam gear allows sufficient movement to produce full torque at "dead" low speed.

Mr. Mountain still appears to be doubtful about the advisability of electric winding. I agree that his conclusions Nos. 1 and 2 of 20 years ago still hold, but there is very little coal available to-day of a lower value than 12s. per ton. His conclusion No. 3 must be modified in view of the enormous increase of the colliery loads other than winding. In Table 2 the winder units are only 12 per cent of the total loads, and even the peaks do not exceed 25 per cent of the average load. His conclusion No. 4 is true of isolated collieries, but if by joint ownership or co-operation a group of collieries can run a large central station or stations, interlinked with waste-heat stations, then a supply company can only compete by virtue of its greater diversity factor. Another factor which tells greatly in favour of centralized power supply and complete electrification is the increased cost and decreased output of labour. Small steam plants are notoriously extravagant of labour, and the costs of this item are seldom given proper consideration in comparative estimates.

In spite of Mr. Mountain's statement with regard to the standard practice of installing steam winders and mixed-pressure turbines in the Doncaster district, no less than five large electric winders have been installed there and three more are on order in the last two years. Further, no steam winder in the country has an output or efficiency equal to that of the Ward-Leonard set described on page 531, i.e. 525 tons per hour from a depth of 650 yards with an efficiency of 64 per cent. This rather disqualifies his statement that electric winders are only suitable for small outputs. I can assure Mr. Mountain that the unit costs in the stations to which I refer are such as to justify considerable capital expenditure in electrifying winders, fans and compressors. A small proportion of these units is generated by waste heat, i.e. gas engines or mixed-pressure turbines. The units generated by mixed-pressure turbo-alternators (which are properly charged with the cost of heat units in the steam supplied to them) cost considerably more than those generated by modern high-pressure turbo-alternators.

Mr. Perry does not agree with my conclusion that it is better to spend money in increasing the generating plant and transmission system than to install flywheels. He speaks from the manufacturers' point of view. My conclusion is based upon several years' operation of a system having nearly 40 large electric winders connected to it, including the two largest flywheel winding sets, the two largest Ward-Leonard sets and the two largest a.c. winder sets in this country. The peak loads which cause the most disturbance in the system are those from the flywheel sets. Referring to Table 4, although the Ward-Leonard output is 12½ per cent higher, its peak load is only 5 per cent higher, due to the very much higher overall efficiency. The assumption that the introduction of a flywheel produces a uniform load demand is never borne out in practice, even when working at full schedule output. Large winders have peaks extending over periods of 15 to 26 seconds, and for complete equalization the flywheel must give out 25 000 to 35 000 kW-seconds (a very different quantity of energy from that required in rolling-mill Ilgner sets). Speed is regained during the braking and banking periods, which may be 30 to 40 seconds. The result is that energy is imparted to the flywheel at low efficiencies of the driving induction motor. Further, the usual slip regulation of 10–15 per cent reduces the motor efficiency during the peak-load period by a corresponding amount. Even without a flywheel the light-load losses of an induction-motor-driven set are 50 per cent higher than those of a synchronous motor at unity power factor, and with a flywheel 100 per cent higher. The extra cost of a 30-ton flywheel complete with shaft, bearings, etc., is about £5 000. The extra cost of generating plant to carry the Ward-Leonard peak would be £2 000 if the actual peak kW were charged for, or nothing if R.M.S. kW were taken. Flywheels are useful for dealing with peak loads of ½ to 2 seconds' duration, but I am of the opinion that peaks of 15 to 25 seconds are better transmitted to the generating plant and thence to the boilers. Mr. Perry advances the Stubbs-Perry scheme as a solution of heavy winding problems, even for a group of collieries. As only one Stubbs-Perry equipment is in operation at the moment and the second set has been ordered with an induction motor as an auxiliary drive to save power in the non-coal-winding shift, I do not propose to discuss the system at the present time but await with interest the operating results. The figure given for the direct-coupled d.c. winder motor on page 529 is the average test figure of several motors of similar output and speed.

Capt. Mackintosh's objections to the Ward-Leonard winders (apparently including a flywheel) that they must be unreliable because of the "number of links in the chain" is not borne out by practice. In 13 years' operation there have only been three stoppages exceeding 15 minutes on two large Ilgner sets. Owing to the arrangement of motors and generators in pairs only one of these stoppages (a fire in the engine room) shut down a winder completely. My experience is that an electric winder is more reliable than a steam winder.

In reply to Mr. Johnson, the actual kW absorbed by a 12 ft. 6 in. diameter 30-ton flywheel running at 485 r.p.m. is about 35. This can be reduced by 50 per cent by the methods Mr. Johnson suggests, but the vacuum-producing apparatus will absorb a portion of this saving.

Mr. Burns and Mr. Mann favour a.c. winders for all purposes. I have found in every case that the consumption per ton for a.c. winders is higher than the calculated figure, more particularly in large equipments dealing with peaks of 2 500 to 3 000 h.p. Loads vary greatly; a tub of rubbish may weigh 75 per cent more than a tub of coal, and Fig. 10 shows what happens with only 12½ per cent variation of load. Their remarks are based upon experience of winders of much smaller size, i.e. 200–500 h.p. and more uniform loads. My conclusions are based upon a very large number of winders in all parts of this country and abroad, and on direct observation of nearly 40 winders of sizes varying from 100 h.p. upwards. Some of these have been in operation for 20 years. This paper refers only to larger machines which I considered would be of greater interest, and more particularly to those with novel features such as the synchronous-motor-driven Ward-Leonard sets or the compressed-air-operated air-break contactors.

The Stjernberg formula or the alternative Table 3 can only be used as a preliminary guide. Up to 500 h.p. (R.M.S.) only exceptional circumstances should necessitate Ward-Leonard; above 1 500 h.p. an a.c. winder is possible on only few systems. The total cost per ton raised is the final factor.

Mr. Mann does not think reverse-current breaking necessary. If he works with Stjernberg coefficients of 0·3 and upwards he will find it an absolute necessity on equipments of 750 h.p. and upwards.

Mr. Burns replies to Mr. Pryce-Jones's query that the Harworth-Stubbs-Perry equipment might have had a.c. control without apparently altering the efficiency.

With regard to the second Stubbs-Perry equipment, out of Mr. Mann's lengthy explanation the fact which I stated emerges, viz. that an induction motor is included with this set to run the motor-generator for light-load winding or occasional trips.

Mr. Mann's analysis of Table 4 overlooks the fact that in the synchronous-motor-driven Ward-Leonard set voltage-drops due to peaks can be corrected by varying the power factor of the load demand. Provision is made for this automatically in my patented device. He further states that a system that can carry a 3 250-h.p. motor can carry a peak of 4 000 h.p. Surely it can also carry a peak of 4 500 h.p., and a flywheel is unnecessary on the Ilgner set.

I have nothing to add to my remarks on tail ropes. I appreciate their advantages and would install them if the mining engineers would accept them.

Mr. Mann's remarks on pot and weir type controllers are very gratifying to one who has for many years favoured the pot type in spite of strong opposition. The two largest a.c. winders in this country have pot-type controllers and air-break contactors and have been running for three years without a hitch.

Mr. Weir questions my figures on the comparative costs of Ward-Leonard and a.c. winders, and Mr. Routledge also questions my figures on geared and ungeared Ward-Leonard main motors. My comparison is based upon a number of actual installations and I cannot agree that a complete Ward-Leonard set costs 75 per cent more than a geared a.c. set.

Here are comparative figures :—

	A.C.	Ward-Leonard	Geared Ward-Leonard
Mechanical parts	67·7	48	67
Electrical parts, including cables	32·3	87	70
	100	135	137

My comparison is made with a single main motor in each case but duplicate generators on the Ward-Leonard motor-generator set.

With reference to Mr. Routledge's comparison of geared and direct-coupled winder motors, taking his ratios and analysing them mathematically on the basis of the proportional costs of electric and mechanical equipment from some 30 tenders, the results are as follows :—

	Single motor	Double motor
	Per cent	Per cent
Percentage value of whole cost, electrical and mechanical gear, of main motor	32	37
Percentage of value of winding portion only, mechanical and electrical	47·8	54·3

From this it would appear that in the case of the double-motor equipment the price of the high-speed electric motors would have to be less than one-third of the price of the low-speed motors, and in the case of the single-motor equipment less than one-fifth. These are impossible values. He must have compared a very expensive type of low-speed motor with a very cheap high-speed motor. It will be seen from the average of a number of tenders that the geared Ward-Leonard equipment was slightly more expensive than the direct-coupled set. I adhere to my opinion that a direct-coupled motor, of equal efficiency, is worth 20 per cent more than a high-speed motor and gearing, and I have not yet been offered a high-speed equipment 10 per cent cheaper than a direct-coupled set. I cannot follow Mr. Routledge's statement with regard to relative efficiencies, as the geared and direct-coupled equipments are exactly equal in efficiency at 105 per cent full load, and the direct-coupled machine has a higher efficiency at all lower loads and a slightly lower efficiency at the higher loads. For the normal winding schedule the efficiencies are practically identical. Again, in comparing the steam consumption of the Harworth flywheel set with that of the Britannia equipment, he has apparently taken the input on light load for the Britannia set and increased it for comparison with the Harworth set in the ratio of the flywheel stored energy. As the actual losses in the flywheel amount to only 35 kW, as will be seen from Table 4 by comparing the third and fourth figures in col. 2, this is hardly fair. A more correct estimate would be as follows: The stored energy of the flywheel is 70 million ft.-lb. and not 55 million as he takes. The light-load losses of the modern 3 200-volt Ilgner set without flywheel are 115 kW, and with flywheel, increasing in the proportion of 70 to 80 million, 156 kW. Losses in transmission are considerably under 5 per cent, as this set is within a mile of the principal power house. Taking the steam consumption per kW which he uses, the actual light-load consumption of this set would be 2 300 lb. per hour, against the Harworth consumption of 3 650 lb. per hour, or 37 per cent lower instead of 26 per cent higher as he states. With a modern Ward-Leonard equipment still more favourable results would be obtained. I do not think that the time is opportune

to discuss the merits of the Stubbs-Perry scheme; this should be postponed for a couple of years, when experience of the actual operating results will be available.

In reply to Mr. Bull, owing to the more uniform speed of the synchronous-motor-driven Ward-Leonard set, control is more definite as compared with that on the Ilgner set, which has a 15 per cent speed-drop.

In reply to Mr. Ashley, the usual power factor of large geared winder motors at full speed is 0·80 to 0·84. A direct-coupled a.c. motor running at 72 r.p.m., under my control, has a power factor of 0·55 at full load. Another of 60 r.p.m. in the South Wales district on a 25-cycle circuit has a power factor of 0·6–0·65.

Mr. Routledge confirms the economy of electric winders as compared with steam winders and mixed-pressure turbines for the 7-hour shift. Where two-shift or even three-shift operation is the custom, as in parts of the Doncaster field, the light-load losses for the steam equipment have less effect and the economy of the electric winder is not so marked, but out of several hundred equipments which I have calculated I have not found a single instance where the steam-winder mixed-pressure turbine equipment is more efficient than the electric equipment, and the operating costs of two collieries almost identical in every respect from the point of view of depth, output and class of coal, one with steam winders and the other an all-electric equipment, show that the electric equipment there effects a very appreciable economy. Anyone who has seen a large steam winder and a large electric winder in operation cannot but be struck by the smooth and simple operation of the electric equipment as compared with that of the steam equipment.

In reply to Mr. Hollingsworth, the capital cost of a completely electrified colliery, together with its proportion of a centralized power scheme, is less than that of a steam-winder mixed-pressure equipment complete with boilers, plant, etc., and, as the figures given show, the operating costs are considerably less. The difference in the light-load losses of the synchronous motor and the plain induction motor for winder motor-generator sets is purely a question of light-load losses. The magnetizing current is practically constant in the induction motor, with resulting high core loss and appreciable stator copper loss at light loads. The synchronous motor runs at unity power factor with minimum excitation low core loss and stator and rotor copper losses. For the same shaft horse-power the induction-motor consumption is nearly twice that of the synchronous motor.

Comparison of steam and electrical collieries.—Mr. Wood supports his partner Mr. Mountain in his championship of the steam-winder mixed-pressure turbine equipment for collieries. He takes *some* of the figures given in Table 5 of the paper and presents a case for a steam-winder mixed-pressure turbine equipment. If this is typical of the methods employed for calculating the coal consumption of collieries, then it is not surprising that colliery owners still install steam winders in spite of the proved greater efficiency of the all-electric equipment. His figure of 3 lb. per unit does not agree with that given in the Electricity Commissioners' Report for the year ending March 1924. Excluding group A, groups B and C, consisting of 36 stations of 200 to 50 million units per annum, have an average consumption of 2·33 lb. per unit generated, but I will take his figure of 2·75 lb. to avoid controversy. He takes a 42-hour week, omitting the men-winding periods, the afternoon and evening shifts and

	Mr. Wood's figures	Actual running figures
H.P. and L.P. steam per hour passed through M.P. turbine, lb.	58 000	58 000
Boiler auxiliaries, condensation, blow-downs, steam blowers, etc., average per hour, lb. ..	—	12 600
Total for 6 coal-winding shifts in one week, 42 hours, lb. ..	2 430 000	2 960 000
Average steam evaporated during afternoon and night shifts, including boiler auxiliaries, etc., per hour, 15 700 lb. over 102 hours	—	1 600 000
Sunday evaporation, M.P. turbine not running	—	380 000
Total steam evaporated by boilers in week of 168 hours, lb.	2 430 000	4 940 000
Coal consumption per week at 7·12 lb. per lb. of coal, lb.	342 000	694 000
tons	152·5	310
Alternative consumption for electric winders, etc.		
Electric winder units	52 500	52 500
Extra units owing to shut-down of M.P. turbine	78 850	78 850
Total additional units required	131 350	131 350
Coal at 2·75 lb. per unit, lb.	362 000	362 000
tons	161·5	161·5
Mr. Wood's calculated extra coal for electric winder proposition .. .. .. tons	9·0	—
Actual reduction in coal consumption by installing electric winders .. .. tons	—	149·5

occasional winds. He also omits all reference to boiler auxiliaries, blow-downs, condensation, etc. I repeat the actual figures already given on pages 534, 535 and 536 compared with Mr. Wood's estimated figures, including the items that he has overlooked and correcting one or two of his small errors. The average boiler efficiency was 74–75 per cent, giving an evaporation of

7·12 lb. per lb. of coal. Babcock boilers with chain-grate stokers and induced draught were used. The winding engines and mixed-pressure turbine were modern engines of the highest class.

That is, instead of an increased consumption of coal of 9 tons (corrected from 12½) as calculated by Mr. Wood, there will be a reduction of 149·5 tons per week based on the present actual coal consumption and the electrical consumption of the winding engines of similar collieries, i.e. 2·46 units per ton net or 4·2 units per ton gross.

In reply to Mr. Harvey, I agree that the choice of the most efficient and suitable winding equipment is a matter for experts. Tables 2, 5, 6, 7 and 8 can be completed by taking a coal consumption per unit to suit the size and load factor of the plant under consideration.

Miscellaneous.—Mr. Sparks and Mr. Sack consider that I have ignored lighting. Professor Thornton last year read a paper * devoted principally to this subject, but we still await the transformers to give the 150 cycles which he advocated. As the power taken for lighting is only ½ of 1 per cent of the total power produced, it is not of great importance in the general scheme of "Electricity in Mines." Further, the same objections are raised to electricity for lighting as for power in certain places. Lighting at the pit bottom and wherever possible has greatly improved in recent years, particularly in regard to the wiring and type of fittings. Miners' lamp bulbs are not so very inefficient as Mr. Sack suggests; 1·5 to 1·8 watts per candle is usual. I agree that 2 volts is too low, as contact and other resistances absorb too high a proportion. A 4-volt lamp is now on the market. Miners' nystagmus has not been finally proved to be entirely due to inadequate illumination. One school of thought attributes it to gases occluded from the coal. Again, replying to Mr. Sack, more than 75 per cent of the compressed air produced is utilized by the actual coal-getter in cutting and conveying.

* *Journal I.E.E.*, 1924, vol. 62, p. 481.

In reply to Mr. Simon, a very large proportion of the underground haulages in South Wales are electrically driven, but the load factor of haulages is very low, varying from 3 to 5, and the proportion of total power taken barely 2½ per cent. I agree that contactor-type reversing-switches reduce the labour of operation considerably, and I have introduced them in several heavy-duty haulages.

Mr. Hodge raises a number of questions. With regard to shaft cables, British-made paper-insulated cables seldom give any trouble. I have not had a 3 300-volt shaft cable fail for many years. Where roof-falls are frequent, double-wire armouring and either steel piping or double D troughing are necessary. Progress in design and improvements in ventilation and other mining methods will eventually allow electricity to be used in every part of the mine.

Mr. Phillips compares the conservatism of the Midlands and South Wales. At present the combined objections of the mines inspectors, colliery managers and miners prevent the extensive introduction of electric mining in the steam-coal measures in South Wales, but electricity is used at the face in house-coal and anthracite collieries. It appears that a similar prejudice exists against electric winding in the Midlands. This prejudice is supported by the absence of any large public supply company or any attempt to group collieries, and also by the fact that accurate records of the steam and coal consumption of steam-winder mixed-pressure equipments are rarely available. A grouping scheme is now in progress, so that electric winding may now have a chance to develop.

Mr. Sparks and Mr. Harvey refer to the importance of reliability in mining plant. The minimum-wage operation is another factor which makes it of the greatest importance. Efficiency is of no value if it is obtained at the expense of reliability.

REPORT OF THE COUNCIL FOR THE YEAR 1924–1925, PRESENTED AT THE ANNUAL GENERAL MEETING OF 7 MAY, 1925.

CONTENTS.

REPORT.

The Council, at the Fifty-third Annual General Meeting of the Institution of Electrical Engineers, present to the members their Report for the year 1924–25, covering approximately the period from 1st April, 1924, to 31st March, 1925, and, in doing so, desire to put on record their gratification at the continued progress and prosperity of the Institution, and also to thank the many members who have so freely placed their services and knowledge at its disposal.

(1) Membership of the Institution.

The changes in the membership since the 1st April, 1924, are shown in a table given in Appendix A.

The following table shows the growth of membership for the last few years:—

Year	Membership	Increase or decrease
1915	6 811	− 234
1916	6 676	− 135
1917	6 613	− 63
1918	6 667	+ 54
1919	7 023	+ 356
1920	8 146	+ 1 123
1921	9 449	+ 1 303
1922	10 275	+ 826
1923	10 911	+ 636
1924	11 415	+ 504
1925	11 743	+ 328

The membership of the Institution still shows an increase which, although much smaller than those of the years immediately following the war, is very satisfactory.

(2) "Chartered Electrical Engineer."

The Council think it useful to include in this Report the contents of a letter which was despatched to all Members and Associate Members on the 5th May, 1924.

Under Bye-law No. 9, which has received the sanction of the Privy Council, every Member and Associate Member of the Institution is entitled to describe himself as a "Chartered Electrical Engineer."

The privilege is one which attaches to the individual member, and if that is borne in mind, little difficulty will arise in making a legitimate use of the title. For example, when the names of all the members of a firm are printed separately on the letter paper of the firm, it would be appropriate that those of them who are Members or Associate Members of the Institution should have the qualification "M.I.E.E." or "A.M.I.E.E." added to their names, followed by the title "Chartered Electrical Engineer." But this should be done in such a way as to make it quite clear that the title applies

individually to certain members of the firm and not to the firm itself.

Similarly, those directors of a company who are Members or Associate Members of the Institution may legitimately make the same individual use of the title "Chartered Electrical Engineer."

The privilege being an individual one, a Member or Associate Member of the Institution should not append the title "Chartered Electrical Engineer" to his signature when he signs a letter or other document on behalf of his firm or company.

A Committee, presided over by the President, has been appointed by the Council to deal with any cases of doubt or difficulty which may arise in connection with the use of the above designation, and all such cases should be referred to the Secretary, who will bring the matter before the Committee for their decision.

The Council feel confident that they will receive the support of the members in preserving the strict use of a title which carries with it an honourable distinction.

(3) Unauthorized Use of the Letters "A.M.I.E.E."

It recently came to the knowledge of Mr. J. Orchiston, the Local Honorary Secretary and Treasurer of the Institution for New Zealand, that a person in that Dominion was falsely representing himself as being a member of the Institution and using the letters A.M.I.E.E. Legal proceedings having been taken, a conviction was secured and the offender was fined £5. The Council have expressed to Mr. Orchiston their appreciation of his action in the matter.

(4) Members Practising as Consultants.

The attention of the Council was recently drawn to an advertisement of a Local Authority in which Chartered Electrical Engineers were invited to submit, in competition with each other, their terms for professional advisory work.

In the opinion of the Council such a proceeding is undesirable and not in the best interests of Local Authorities requiring advice. The Council would consider it to be a breach of professional etiquette for a member of the Institution to reply to such an advertisement.

Where the names of a sufficient number of qualified consultants are not known to a Local Authority, the President of the Institution will always be willing to submit the names of qualified electrical engineers for the purpose.

A statement to the above effect appeared in the issue of the *Journal* for January 1925 (p. 153).

(5) Mascart Medal.

In April 1924 the Council received an intimation from the Société Française des Electriciens to the effect that the Society had founded a Medal of Honour to be called the Mascart Medal, in memory of that eminent French scientist, the Medal to be awarded triennially to scientists or engineers distinguished for their work in pure and applied electricity, whatever their nationality.

The Society also intimated that the first (1924) award of the Medal had unanimously been made to Monsieur A. Blondel, and requested that members of the Institution be informed of the founding of the Medal and of its award to Monsieur Blondel.

(6) Examinations.

The Associate Membership Examination was held in April and October, 1924, in London, Belfast, Birmingham, Cardiff, Glasgow, Manchester and Newcastle-on-Tyne, and also in Spain, New Zealand, South Africa and the Argentine. The candidates examined included a number of officers of the Corps of Royal Engineers, who sat for the examination for the purpose of qualifying for "Engineer Pay."

For the purpose of qualifying for "Signal Pay," officers of the Royal Corps of Signals were also examined by the Institution in the "Theory of Electrical Military Signalling" at the Signal Service Training Centre, Maresfield Park Camp, Sussex, in August 1924 and February 1925.

A certain number of candidates submitted theses and papers during the year in lieu of the Examination.

(7) Honorary Members.

The Council have pleasure in recording that, as announced at the Ordinary Meeting on the 6th November, 1924, they have elected Sir Oliver Lodge, D.Sc., F.R.S., to be an Honorary Member of the Institution.

Sir Oliver Lodge became a Member of the Institution in 1889 and was Chairman of the Birmingham Local Section in 1901–2, and Vice-President of the Institution in 1902–4.

There are now ten Honorary Members.

(8) Honours and Distinctions Conferred on Members.

Knighthood.

Longbottom, B. (Member).

C.M.G.

im Thurn, J. K., Capt. R.N. (Member).

(9) Faraday Medal.

The fourth award of the Faraday Medal has been made by the Council to Sir J. J. Thomson, M.A., O.M., F.R.S., Honorary Member.

(10) War Memorial.

The War Memorial Book containing the biographical notices of the 162 members of the Institution who fell in the war of 1914–1919 was published in April 1925, and copies have been presented on behalf of the subscribers to the War Memorial Fund to the nearest relative of each fallen member. It is a large post-folio volume ($15\frac{1}{2}$ in. × 10 in.) bound in special buckram, and contains 345 pages of letterpress set in twelve-point old-style type and 159 portraits.

The biographical notices are preceded by a historical introduction entitled "The Origin and Causes of the Great War, 1914–1919," written by the editor of the Book, Lieut.-Col. W. A. J. O'Meara, C.M.G., R.E. General Service maps of the battle fronts mentioned in the book are included in a pocket at the end of the volume.

Additional copies of the book have been printed,

which will be on sale to members and the public at the price of £2 2s. each, and the proceeds will go to the War Memorial Fund. A specimen copy can be seen in the Library.

The Council again desire to take this opportunity of expressing their appreciation of the very thorough and able manner in which Colonel O'Meara has edited the volume.

(11) Deaths.

The Council regret to have to record the death of the following 68 members of the Institution during the year :—

Honorary Member.

Heaviside, O., F.R.S.

Members.

Awoki, D.
Bainton, J. R.
Bastian, C. O.
Bhering, F.
Birks, L.
Bonnor, G. F.
Bradfield, W. W., C.B.E.
Brown, C. E. L.
Cappel, Sir A. J. L., K.C.I.E.
Carr, Col. G. A., R.E.
Cook, D.
Hayward, R. F.
Hunter, W. D.
Jensen, J. L. W. V.
Langdon-Davies, W.
Madgen, W. L.
Markby, W.
Martin, T. C.
Oi, S.
Pletts, J. St. Vincent.
Robertson, W. S.
Sullivan, H. W.
Tamaki, B.
Tasker, W. H.
Thompson, P. S.
Walmsley, Prof. R. M., D.Sc., F.R.S.E.
Wordingham, C. H., C.B.E.

Associate Members.

Balsillie, J. G.
Bedford, A. L.
Bowman, H. M.
Brander, G.
Bullock, H. J.
Canning, R. W.
Chamen, A. D.
Conning, W. D.
Cooke, R. R.
Dearling, G. S.
Dutta, S. K.
Farrar, R. R.
Fleming, G.
Forder, E.
Gill, R. F. H.
Gordon-Campbell, W. F.
Hale, C. P.
Hedley, E.
McMorrough, F.
Richardson, O. A.
Robertson, J.
Robinson, W. M.
Rorke, Major A., M.C., R.E.
Sergent, R. S. B.
Toppin, W. A.
Utting, Major S.
Woodfin, N. C.

Graduates.

Crook, E. R.
Gerry, L. F.
Todd, W. M.

Students.

Gibb, C. J.
Grute, L. H.
Mitton, A. R. D.
Nisbet, C.
Slattery, L.

Associates.

Cuff, J. C.
Drummond, Sir H. H. J. W., Bart., Brig.-Gen., C.M.G.
Moulsdale, W. E.
Ogilvie, Sir A. M. J., Colonel, K.B.E., C.B., V.D., R.E.(T.).
Powles, W.

(12) Institution Building.

A very large number of kindred societies have continued to hold their meetings in the Institution building during the past twelve months and it has been a pleasure to the Council to have been able to grant the use of the premises for this purpose.

(13) Papers.

For the information of members and to remove any possible misapprehension, the Council think it desirable to include in this Report an outline of the procedure followed in connection with papers.

The final decision in regard to the acceptance or rejection of a paper lies in the hands of the Papers Committee, which consists of the eight Chairmen of the Local Centres and seven other Members of Council. Each paper received is submitted to two or more referees, and care is taken in selecting these referees that they should be in a position to consider the subject matter of any particular paper from the point of view of the general body of members rather than from a highly specialized aspect.

These referees do not see each other's reports, but their reports, together with the paper, are submitted to a member of the Papers Committee, who at the beginning of the session is selected to be the Committee Referee for all papers falling under the particular subject allotted to him. The Committee Referee next reports to the Papers Committee, which comes to a final decision after consideration of all the reports.

As regards the obtaining of papers, the Papers Committee is in close collaboration with the Committees of the Local Centres and the Sectional Committees of the Institution. It may be useful to state here that there are five Sectional Committees and that they deal with the following subjects respectively : Lighting and Power, Traction, Telegraphs and Telephones, Electricity in Mines, Electro-Chemistry and Electro-Metallurgy.

The selection of papers for the Wireless Section is in the hands of the Wireless Section Committee.

The Council take this opportunity of expressing their grateful thanks to the Chairmen of Local Centres for their regular attendance at the meetings of the Papers Committee, thereby ensuring efficient contact and co-operation between the Committee itself and the Committees of the Local Centres in the important question of papers.

The Council will be pleased to consider any constructive suggestions that may occur to members for the improvement of the papers read before the Institution, either as regards subject matter or method of presentation.

(14) Meetings.

During the past twelve months, 365 meetings have been held in London and the Local Centres by the members, the Council and the various Committees. A detailed statement is given in Appendix B.

The Premiums awarded by the Council for papers will be announced about the time of the Annual General Meeting.*

* See Institution Notes, page 613.

(15) LOCAL CENTRES AND SUB-CENTRES.

Reports from the Committees of the Centres and Sub-Centres indicate that the attendances at the meetings and the interest in the discussions have been well sustained.

The President has attended functions or meetings at the Centres at Birmingham, Bristol, Dublin, Glasgow, Leeds, Liverpool, Manchester and Newcastle, and the Sub-Centres at Sheffield and Loughborough. On each occasion he has addressed the members and was gratified to note evidence of continued activity and development and of appreciation by the members attached to the various Centres of the opportunities afforded for discussion and intercourse.

(16) WIRELESS SECTION.

The interest and activities of the Wireless Section have been well maintained. Seven meetings have been held, at which nine papers were read.

(17) INFORMAL MEETINGS.

Fourteen meetings have been held during the session and the average attendance was 59, an increase of nine over last year.

The subjects discussed have stimulated a lively interest and many have taken part in the discussions who only rarely, if ever, take part in the discussions at the Ordinary Meetings.

(18) STUDENTS' SECTIONS.

There are at present 3 841 Students on the Register of the Institution, and the eight Students' Sections, viz. at London, Birmingham, Glasgow, Leeds, Liverpool, Manchester, Newcastle and Sheffield, have carried out a very full programme of meetings, visits to works and social functions.

Addresses to the London Students' Section were given by the President and Sir James Devonshire, K.B.E., Vice-President.

In August last the Students' Sections organized a visit to France at the invitation of the Société Française des Electriciens. Lyons was chosen as the venue and, through the courtesy of Mr. J. Grosselin, Local Honorary Secretary of the Institution in France, and Mr. Dumont of the Société Française des Electriciens, a very attractive programme was arranged for the 26 Students who took part.

The programme included visits to the following places :—

A Thury direct-current system operated by the Société Générale de Force et de Lumière.
Mouche central station.
Annual International Fair, Lyons.
Silk factory of Messrs. Vital Matthieu and Sons.
Works of the Berlier Motor Company.
Beaujolais vineyard.
120 000-volt system of the Compagnie Electrique de la Loire et du Centre, at St. Etienne.
Coal mines of the Loire.
Lyons radio station.

The firms and public bodies whose works, etc., were visited have been thanked for their generous hospitality, and the Council have to thank Messrs. J. H. Reyner and G. R. A. Murray of the London Students' Section for their valuable work in organizing the Visit.

(19) FARADAY LECTURES.

With a view to increasing the interest of the general public in electrical matters, the Council instituted in 1923 the Faraday Lectures of the Institution. These Lectures, which are delivered at selected Local Centres, are open to the public by means of admission cards obtainable through members of the Institution. The first five Lectures were delivered during the Session under review by Professor G. W. O. Howe, D.Sc., at Birmingham, Edinburgh, Leeds, Manchester and Newcastle, his subject being "World-Wide Radio Telegraphy."

Making allowances for the fact that this was the first occasion on which the Lectures were delivered, the attendances on the part of the public were very satisfactory, and it is hoped that as the Lectures become better known still larger attendances will be recorded.

(20) SCHOLARSHIPS.

The following Scholarships have been awarded by the Council :—

A David Hughes Scholarship.

(Value £50 ; tenable for one year.)

H. E. W. Tumath (Municipal College of Technology, Belfast).

A Salomons Scholarship.

(Value £50 ; tenable for one year.)

E. Youel (Liverpool University).

War Thanksgiving Education and Research Fund (No. 1).

A grant of £100 for educational purposes has been made this year by the Council, under the provisions of the Trust Deed, to A. E. Morrill [City and Guilds (Engineering) College, London].

(21) CONVERSAZIONE.

The Annual Conversazione was held at the Natural History Museum, South Kensington, London, on the 26th June, 1924, when about 1 400 members and guests attended.

(22) ANNUAL DINNER.

The Annual Dinner was held at the Hotel Cecil, London, on the 12th February, 1925, the members and guests present numbering 522.

An Account will be found in the *Journal*, vol. 63, p. 490.

(23) VISIT OF OVERSEAS ELECTRICAL ENGINEERS.

There was no Summer Meeting in 1924. In place of it, since many engineers from overseas were present in England for the British Empire Exhibition, the World Power Conference and the Kelvin Centenary Celebra-

tions, the occasion was thought suitable to entertain delegates and ladies from kindred societies overseas. The Council accordingly invited the following bodies to send delegates to be the guests of the Institution :—

- American Institute of Electrical Engineers.
- Asociacion de Ingenieros de Caminos, Canales y Puertos, Madrid.
- Asociacion Nacional de Ingenieros Industriales, Madrid.
- Association Suisse des Electriciens.
- Associazione Elettrotecnica Italiana.
- Dansk Ingeniorforening, Denmark.
- Engineering Institute of Canada.
- Institution of Engineers (India).
- Institution of Engineers, Australia.
- Koninklijk Instituut van Ingenieurs, Holland.
- Norske Ingeniorforening, Norway.
- Société Belge des Electriciens.
- Société Française des Electriciens.
- South African Institute of Electrical Engineers.
- Svenska Teknologföreningen, Sweden.
- Verseniging van Directeuren van Electricteitsbedrijven in Nederland.

The visit took place from the 10th to the 15th July, 1924, and about 170 delegates and ladies participated, the Council of the Institution and past Members of Council acting as hosts. Many of the party having arrived in England some days earlier, a large number were able to accept a gracious invitation from Their Majesties to be present at a Garden Party held by the King and Queen at Buckingham Palace on the 5th July.

On the 10th July the visitors were formally received by the then President (Dr. A. Russell) in the Institution Building and entertained at a luncheon at the Hotel Cecil. A large number of members and ladies were also present at both the reception and the luncheon. In the afternoon the visitors heard the Kelvin Oration delivered at the Institution of Civil Engineers by Sir J. J. Thomson, O.M., F.R.S.

The British Empire Exhibition was visited the following day, and in the evening the delegates attended the Kelvin Centenary Banquet at the Connaught Rooms.

With the exception of Sunday, the 13th July, when parties attended the morning services at Westminster Abbey and St. Paul's Cathedral and visited the Zoological Gardens in the afternoon, the remainder of the visit was spent in excursions to Cambridge (12th July), Birmingham and Stratford-on-Avon (14th July), and Chiswick and Windsor (15th July). During these days the party inspected the Cavendish Laboratory, the Colleges and other places of interest in Cambridge, the Nechells power station of the Birmingham Corporation and the University Engineering Laboratories at Birmingham, places of interest at Stratford-on-Avon, the Chiswick overhaul works of the London General Omnibus Company, Ltd., and the State Apartments at Windsor Castle. The visit concluded with a Joint Conversazione at the Institution of Civil Engineers by invitation of the Councils of the Institutions of Civil, Mechanical and Electrical Engineers.

The Council have expressed the cordial thanks of the Institution to those whose hospitality was extended to the visitors during the period of the visit, including the Master and Fellows of Trinity College, Cambridge, the Vice Chancellor of Cambridge University, the Lord Mayor of Birmingham, the London Midland and Scottish and the London and North Eastern Railway Companies, and Lord Ashfield.

(24) Cavendish Laboratory.

As was announced at the Ordinary Meeting on the 23rd October, 1924, the Council have made a donation of 100 guineas to the Cavendish Laboratory, Cambridge, as a token of their appreciation of the immense value of the electrical researches carried out at the Laboratory by Sir Joseph Thomson, Sir Ernest Rutherford and other Cambridge physicists.

(25) Paris International Conference on Large E.H.T. Electric Supply Systems.

During the Session the Council appointed a special Committee to ensure representation of British views and interests at the above Conference, which has been arranged to take place in Paris in June 1925. The following is a list of the papers to be presented at the Conference by British authors :—

Author.	*Title of Paper.*
H. W. Clothier ..	Metal-clad Switchgear and Isolation of Faults.
F. H. Clough ..	Transmission of Electric Power over Long Distances.
A. R. Everest ..	Insulating Oils. A Review of Research Work in Great Britain.
R. W. Gregory ..	Substation Design, with particular reference to Metal-clad Switchgear.
J. L. Langton ..	Developments in Porcelain Line Insulators.
R. Borlase Matthews	Rural E.H.T. Distribution.
A. Page	The Re-organization of Electricity Supply in Great Britain as governed by the Electricity Commission.
G. V. Twiss ..	Consideration of Assumed Loadings in their relation to Safety of Overhead Lines.

The following British delegates have already been appointed by the Council, and others may be appointed later :—

Mr. W. B. Woodhouse (Chief Delegate).
Mr. A. R. Everest.
Mr. P. V. Hunter, C.B.E.
Mr. A. Page.
Mr. E. B. Wedmore.

(26) Wireless Telegraphy and Signalling Bill.

Being of opinion that some of the provisions of the above Bill, unless modified, will prove a hindrance not

only to the progress of wireless telegraphy and radio science, but also to electrical and physical research and to the progress of electrical science generally, the Council have made representations to the Postmaster-General in regard to some of the clauses. The matter is still under consideration, and the Bill has not proceeded beyond the stage of first reading.

(27) University of Brussels.

In response to an invitation from the Council and Faculty of the University of Brussels, Mr. Ll. B. Atkinson, Past-President, represented the Institution at the Ceremonies held to commemorate the 50th anniversary of the founding of the École Polytechnique (School of Technology) on the 20th, 21st and 22nd November, 1924.

(28) Norwegian Engineering Society.

Mr. M. L. Kristiansen represented the Institution at the celebration at Kristiania on the 7th, 8th and 9th December, 1924, of the 50th anniversary of the foundation of the Norwegian Engineering Society.

(29) Rensselaer Polytechnic Institute.

The Institution was represented by Mr. J. W. Lieb at the celebration of the 100th anniversary of the foundation of the Institute at Troy, New York, on the 3rd and 4th October, 1924.

(30) University of Leeds.

The Coming-of-Age of the University of Leeds and the Jubilee of its parent foundation, the Yorkshire College, were celebrated at Leeds from the 15th to the 20th December, 1924. The Institution was represented at the functions by Mr. W. B. Woodhouse (President of the Institution) and Mr. T. B. Johnson (Chairman of the North Midland Centre).

(31) Library.

During the year 295 books and pamphlets have been presented to the Reference Library by members and others, and 226 volumes have been purchased. A slight decrease in attendance is recorded, the total number for the year being 2 419, of whom 108 were non-members, as against the total of 2 526 in 1923–1924.

The Council have pleasure in recording the continued circulation of books from the Lending Library, to which 89 new volumes have been added during the year. During the year, 2 184 were issued to 872 borrowers, the corresponding numbers for the previous year being 2 232 and 897 respectively.

A new edition of the Lending Library Catalogue with a subject guide to authors is in preparation and will be issued in the course of the next few months.

(32) The Institution of Gas Engineers.

As a token of appreciation of the facilities placed at their disposal for the holding of their Annual General Meeting in June 1924, in the Institution Building, the Council of the Institution of Gas Engineers have presented to the Institution a photogravure plate for a certificate placing on record his tenure of the office to be issued to each President. The formal presentation of the plate and of the first certificate struck from it was made by the President of the Institution of Gas Engineers at the Ordinary Meeting held on the 22nd January, 1925.

(33) Gifts to the Institution.

The Council have pleasure in recording the following gifts to the Institution and in expressing their cordial thanks to the donors :—

Donor.	*Gift.*
Colonel R. K. Morcom	Bronze statuette of the late Sir Joseph Swan.
Mr. H. Moss	An original Graham Bell telephone licence.
Executors of the late Mrs. Hugh Carter	Oil painting of the late Sir Francis Ronalds, F.R.S.
Physical Society of London	Copy of photograph taken on the occasion of the Society's Jubilee Celebrations on the 21st March, 1924.
Mr. Ll. B. Atkinson ..	Set of prints illustrating the work of laying the first Atlantic cable.
Dr. J. A. Fleming ..	Portraits of himself, Clerk Maxwell and Edison.
Mr. G. W. Partridge ..	An early 10 000-volt transformer.

(34) Electrical Appointments Board.

The number of applicants for posts registered on the 31st March, 1925, was 78, against a total of 114 last year.

A classified Register of members seeking positions, containing particulars of their training and experience, is available for inspection at the Institution offices, and the Secretary of the Board will gladly put employers in touch with highly qualified electrical engineers.

The Council earnestly hope that members who are in a position to assist will not fail to make use of the Register.

(35) The Journal of the Institution.

The Volume of the *Journal* for 1924 comprised 1 006 pages, as compared with 1 204 in the previous Volume.

The net cost of printing and posting the *Journal* in 1924, after allowing for sales and the revenue received from advertisements, was £3 078, as compared with £4 159 in 1923. The net cost per page works out at £3·06, as against £3·45 for 1923, in spite of the fact that the number of copies printed increased from 11 400 in 1923 to 12 000 in 1924. The reduction in the cost of the *Journal* is mainly due to the increase in the advertisement revenue, only nine months' revenue from this source having been included in the 1923 Accounts.

(36) "Science Abstracts."

The Physics volume of *Science Abstracts* for 1924 contained 150 pages more than for 1923, and the

Electrical Engineering volume was of the same size as in the previous year. The Accounts show that the net cost of the publication to the Institution in 1924 was only £68, which the Council consider satisfactory.

(37) Wiring Regulations.

The revised edition (8th Edition) of the Wiring Rules, now published under the title of "Regulations for the Electrical Equipment of Buildings," was issued during the summer of 1924. The Committee have received from members a number of suggestions for the amendment of certain of the Regulations and there have also been discussions at Informal Meetings in London and at some of the Local Centres. The principal criticisms received are due to misunderstandings in regard to the intention of some of the Regulations, but a few questions of principle are also involved.

The Committee are considering the desirability of recommending the Council to amend the wording of a number of the Regulations with a view to removing the misunderstandings as far as possible and taking into account the points of principle which have been raised.

(38) Electricity Regulations.

The Electricity (Supply) Regulations Committee are engaged in preparing suggestions for a revision of the Electricity Commissioners' Regulations (A) for securing the safety of the Public, and (B) for ensuring a proper and sufficient supply of Electrical Energy. It is hoped that a Report thereon will be ready for submission by the Council to the Commissioners at an early date.

(39) Committee on Electricity in Agriculture.

The Report of the above Committee is nearly ready and will be presented to the Council at an early date.

(40) National Certificates and Diplomas in Electrical Engineering.

For the final examinations of the year 1924 the joint Standing Committee representing the Board of Education and the Institution approved 53 courses at schools and colleges for the award of Ordinary Certificates in Electrical Engineering, 15 for the award of Higher Certificates, 4 for the award of Ordinary Diplomas and 2 for the award of Higher Diplomas.

The final examinations were held during the summer of 1924 and the numbers of certificates and Diplomas awarded were as follows:—

282 Ordinary Certificates (including 103 distinctions).
43 Higher Certificates (including 14 distinctions).
9 Ordinary Diplomas (including 22 distinctions in individual subjects).
5 Higher Diplomas (including 3 distinctions).

(41) Benevolent Fund.

The Committee of Management of the Benevolent Fund of the Institution report that on the 31st December, 1924, the Capital Account of the Fund stood at £9 969 11s. 3d., and the accumulated income at £1 889 7s. 5d. The donations and subscriptions to the Fund in 1924 amounted to £1 152 7s. 10d.

In the course of 1924, 78 grants were made to 26 persons, amounting to a total of £1 322 16s. 6d.

(42) Annual Accounts.

Excess of Income over Expenditure.—After making provision for contingencies, as in the previous year, there is a margin to the good on the Revenue Account for 1924 of £2 925 0s. 8d. This amount, which has been carried to the credit of the General Fund, compares with £3 957 11s. 7d. in 1923. The decrease of £1 032 10s. 11d. was chiefly due to the reduction in subscriptions, which came into operation on the 1st January, 1924.

Mortgage.—

	£	s.	d.
In the Accounts for 1923 this stood at	14 801	19	4
Amount of repayments during the year	1 080	17	4
The amount now stands at	£13 721	2	0

Assets.—Taking the Tothill-street property and the investments at cost, and the Institution Building and lease, the library and furniture, etc., at the values standing in the books after writing off depreciation—

	£	s.	d.
the Assets amount to	139 485	15	5
against Liabilities	6 469	14	6
leaving a surplus of	133 016	0	11
which, in comparison with that of the year 1923, viz.	125 399	3	0
shows an improvement of	£7 616	17	11

The balance of £133 016 0s. 11d. is made up as follows:—

Assets.

	£	s.	d.	£	s.	d.
Properties—						
Institution Building and Tothill-street Property	92 289	3	11			
Less Mortgage ..	13 721	2	0			
				78 568	1	11
Investments, Cash, etc.				52 715	13	4
Stock of Paper, Libraries and Furniture ..				8 202	0	2
				£139 485	15	5
Less *Liabilities.*						
Trust Fund Income Accounts	325	17	6			
Sundry Creditors ..	4 502	12	10			
Repairs Suspense Account	1 208	12	1			
Subscriptions received in advance	432	12	1			
				6 469	14	6
				£133 016	0	11

(43) THE INSTITUTION AND BODIES ON WHICH IT IS REPRESENTED.

Appendix C shows in diagram form the organization of the Institution and the bodies on which it is represented.

APPENDIX A.

MEMBERSHIP OF THE INSTITUTION.

The changes in the membership since 1st April, 1924, are shown in the following table :—

	Hon. Mem.	Mem.	Assoc. Mem.	Grad.	Studt.	Assoc.	Total.	TOTAL.
Totals at 1 April, 1924	10	1 862	4 733	1 198	3 244	368		11 415
Additions during the year :—								
Elected	..	11	65	127	675	1	879	
Reinstated	..	6	8	3	19	2	38	
Transferred to	1	53	82	130	..	..	266	
Total	1	70	155	260	694	3	1 183	
Deductions during the year :—								
Deceased	1	27	27	3	5	5	68	
Resigned	..	12	27	25	71	12	147	
Lapsed	..	11	84	60	209	10	374	
Transferred from	..	1	52	38	172	3	266	
Total	1	51	190	126	457	30	855	
Net Increase	..	..	..	..	..	..	..	328
Totals at 1 April, 1925	10	1 881	4 698	1 332	3 481	341		11 743

APPENDIX B.

MEETINGS.

The following is a list of the meetings held during the past twelve months :—

Ordinary Meetings ..	14
Wireless Sectional Meetings	7
Informal Meetings ..	14
Council Meetings ..	16
Local Centres :—	
Irish	6
Mersey and North Wales (Liverpool) ..	8
North-Eastern ..	13
North Midland ..	10
North-Western ..	12
Scottish	10
South Midland ..	8
Western	9
Local Sub-Centres :—	
Dundee	7
East Midland ..	10
Sheffield	7
Tees-side	6
Students' Sections :—	
London	9
Birmingham	8
Leeds	12
Liverpool	8
Manchester	11
Newcastle	13
Scottish	7
Sheffield	5
Committees :—	
Benevolent Fund ..	8
Electricity in Agriculture	2
Committees (*cont.*) :—	
Electricity (Supply) Regulations ..	15
Electro-Chemistry and Electro-Metallurgy	1
Examinations (and Sub-Committee) ..	8
Finance (and Sub-Committee) ..	10
General Purposes (and Sub-Committee) ..	14
Informal Meetings ..	8
Lighting and Power ..	1
Local Centres ..	2
Membership	7
Model General Conditions (and Sub-Committee) ..	2
Papers	10
"Science Abstracts"	7
Ship Electrical Equipment (and Sub-Committee) ..	2
Telegraphs and Telephones	2
Traction	1
Wireless Section ..	5
Wiring Rules (and Sub-Committees) ..	13
Other Committees ..	17
Total ..	365

APPENDIX C.

THE INSTITUTION OF ELECTRICAL ENGINEERS.

- Ordinary Meetings
- Wireless Sectional Meetings
- Informal Meetings
- Meetings of London Students' Section

COUNCIL.

Local Centres.

- Argentine
- China
- Irish
- Mersey and North Wales (Liverp'l)
  - †Liverpool S.S.
- North-Eastern
  - *Tees-side S.C.
  - †North-Eastern S.S.
- North Midland
  - †North Midland S.S.
  - *Sheffield S.C.
  - †Sheffield S.S.
- North-Western
  - †North-Western S.S.
- Scottish
  - *Dundee S.C.
  - †Scottish S.S.
- South Midland
  - *East Midland S.C.
  - †South Midland S.S.
- Western

* S.C.=Sub-Centre.
† S.S.=Students' Section.

COMMITTEES.
(*Standing.*)

Benevolent Fund
Electrical Appointments Board
Examinations
Finance
General Purposes
Informal Meetings
Library
Local Centres
Membership
Papers
Paul Scholarship
" Science Abstracts "
Ship Electrical Equipment
Wireless Section
Wiring Rules

Sectional Committees.
- Electricity in Mines
- Electro-Chemistry and Electro-Metallurgy
- Lighting and Power
- Telegraphs and Telephones
- Traction

COMMITTEES.
(*Special.*)

Electricity in Agriculture
Electricity (Supply) Regulations
Examinations Sub-Committee
Model General Conditions
Proving House

BODIES ON WHICH THE INSTITUTION IS REPRESENTED.

Alloys of Iron Research (Royal Society)
Birmingham Chamber of Commerce
Bradford Public Libraries Committee
Bristol University
British Cast Iron Research Association
British Electrical and Allied Industries Research Association
British Electrical Development Association
British Engineering Standards Association
British National Committee of the International Electrotechnical Commission
British National Illumination Committee of the International Illumination Commission
Corrosion Research Committee of Institute of Metals
Engineering Joint Council
Fifth International Road Congress, 1926
Imperial College of Science and Technology, Governing Body
Imperial Mineral Resources Bureau Conference
Institution of Civil Engineers, Engine and Boiler Testing Committee
Institution of Heating and Ventilating Engineers, Utilization of Exhaust Steam and Waste Heat Committee
Leeds Civic Society
Leeds Municipal Technical Library Committee
Loughborough Technical College Advisory Committee
Metalliferous Mining (Cornwall) School, Governing Body
Middlesbrough Technical College, Governing Body
Mines Department, Electrical Storage Battery Locomotive Committee
National Committee for Physics (Royal Society)
National Committee on Radio Telegraphy (Royal Society)
National Physical Laboratory, General Board
National Register of Electrical Installation Contractors
Newcastle-upon-Tyne Chamber of Commerce
Paris Conference on E.H.T. Lines, 1925
Professional Classes Aid Council
Radiographers, Society of
Röntgen Society Advisory Committee for British X-Ray Industry
Royal Engineer Board
Royal Sanitary Institute Congress, 1925

(*Continued at foot of col. 1.*)

(*Continued from foot of col. 3.*)

Scientific and Industrial Research Advisory Council, Engineering Committee
Standing Joint Education Committee for National Certificates in Electrical Engineering
Transport, Ministry of, Advisory Panel
Union of Lancashire and Cheshire Institutes, Panel for Engineering
Women's Electrical Association
Women's Engineering Society

THE INSTITUTION OF ELECTRICAL ENGINEERS.

REVENUE ACCOUNT FOR THE YEAR ENDED 31ST DECEMBER, 1924.

Dr.

EXPENDITURE.

Year ended 31 Dec., 1923.* £ s. d.		£ s. d.	£ s. d.
	To MANAGEMENT :—		
	Salaries and Wages (including Staff Provident Scheme and War Bonus) ...	10,850 9 1	
	National Insurance	63 18 6	
	Audit Fee	42 0 0	
	Printing	319 10 9	
	Stationery and Office Requisites	501 6 6	
	Addressing	35 2 9	
	Postage of Correspondence and Notices	611 15 8	
	Telephone	66 7 5	
	Travelling Expenses	136 10 7	
	Bank Charges	16 18 6	
12,052 17 2			12,643 19 9
	„ INSTITUTION BUILDING :—		
	Ground Rent	2,201 0 0	
	Rates and Taxes	2,892 12 7	
	Heating	499 17 5	
	Lighting and Power	289 13 3	
	Insurance	158 6 3	
	Reserve for Repairs	1,500 0 0	
	Household Requisites and Cleaning ...	242 5 5	
	New Boilers, Accommodation, etc. ...	1,615 14 1	
		9,399 9 0	
	Less Rents from Tenants	5,541 5 0	
2,829 15 8			3,858 4 0
655 3 4	„ INTEREST ON MORTGAGES		594 15 1
150 19 0	„ FURNITURE AND FITTINGS (Repairs and Renewals) ...		64 15 0
	„ JOURNAL :—		
	Printing	5,170 13 3	
	Postage	1,567 19 1	
	Wrappers and Envelopes	187 3 5	
		6,925 15 9	
	Less Sales and Advertisements... ...	3,847 8 4	
4,171 8 0			3,078 7 5
108 8 9	„ LENDING LIBRARY (Books, Printing, Postage, etc.) ...		126 11 0
	„ SCIENCE ABSTRACTS :—		
	Salaries, Abstracting, Printing, Postage, etc....	4,448 13 3	
	Less Subscriptions, Sales, and Advertisements	4,380 1 11	
27 11 2			68 11 4
	Carried Forward		£20,435 3 7

INCOME.

Cr.

Year ended 31 Dec., 1923.* £ s. d.		£ s. d.	£ s. d.
32,197 5 5	By SUBSCRIPTIONS		30,223 4 7
871 10 0	„ ENTRANCE FEES AND VELLUM DIPLOMA FEES		745 10 0
1,769 10 1	„ DIVIDENDS AND INTEREST		2,115 2 10
247 18 3	„ MODEL GENERAL CONDITIONS		212 4 0
3 14 0	„ WIRING REGULATIONS		92 4 11
8 11 4	„ SHIP WIRING REGULATIONS		10 5 5
	„ TOTHILL STREET PROPERTY :—		
	Rents from Tenants	1,306 4 4	
	Less Ground Rent, Repairs, Alterations, Rates, Taxes, etc.	797 3 11	
889 19 2			509 0 5
	„ EXAMINATIONS :—		
	A.M.I.E.E. Examination (Fees, *less* Expenses)	63 0 3	
	National Certificates and Diplomas (Fees *less* Expenses)	191 5 0	
185 17 3			254 5 3
	Carried Forward		£34 161 17 5

REVENUE ACCOUNT—*continued.*

Dr. EXPENDITURE—*continued.*

*		£ s. d.	£ s. d.
	Brought Forward	...	20,435 3 7
	To Institution Meetings :—		
	Advance Proofs	154 8 4	
	Reporting	126 0 0	
	Grant to London Students' Section ...	30 16 5	
	Honorarium to Kelvin Lecturer	25 0 0	
	Refreshments, Assistance, etc.	239 10 11	
	Travelling Expenses of Authors of Papers	42 6 6	
	Faraday Lectures	66 4 3	
598 17 8			684 6 5
	„ Local Centres :—		
	Money Grants (including Travelling Expenses of Authors of Papers) ...	2,065 4 9	
	Travelling Expenses	588 19 5	
2,410 1 4			2,654 4 2
205 9 2	„ Premiums for Papers	... ...	204 2 3
	„ Special Grants :—		
	British Engineering Standards Association	250 0 0	
	Electrical Research Association... ...	500 0 0	
	National Illumination Committee ...	40 0 0	
	Journal of Scientific Instruments ...	100 0 0	
	British Science Guild	20 0 0	
516 5 0			910 0 0
94 19 5	„ Annual Dinner	... ...	137 4 0
507 13 9	„ Conversazione...	... ...	525 18 10
51 10 0	„ Legal Expenses	... ...	43 18 0
57 1 0	„ Miscellaneous Expenses	... ...	68 13 10
24,573 15 11			25,663 11 1
	„ Amounts Transferred to :—		
277 12 2	Sinking Fund (Premiums for Redemption of Cost of Building and Lease) ...	277 12 2	
4,500 0 0	Reserve Fund (Contingencies and Mortgage Redemption)	3,500 0 0	
	General Fund :—		
1,036 7 1	Obligatory Repayment to Economic Life Assurance Society	1,080 17 4	
	Expenditure on—		
127 16 11	Books and Binding for Library ...	323 15 11	
1,701 1 10	Furniture, Fittings and Apparatus	391 0 3	
3,957 11 7	**Balance carried to General Fund** ...	2,925 0 8	
			8,498 6 4
36,255 7 10			£34,161 17 5

INCOME—*continued.* **Cr.**

*		£ s. d.
	Brought Forward	34,161 17 5
36,255 7 10		£34,161 17 5

* These columns do not add up to the totals of Income and Expenditure shown, as some of the items in the Accounts for 1923 did not occur in 1924.

BALANCE SHEET, 31ST DECEMBER, 1924.

Dr. LIABILITIES.

	£ s. d.	£ s. d.
To Economic Life Assurance Society :—		
On Mortgage of Institution Building (1909)	26,000 0 0	
Since repaid	12,278 18 0	
		13,721 2 0
" Kelvin Lecture Fund :—		
As per last Balance Sheet		648 13 0
" Uninvested Balances of Trust Funds		325 17 6
" Sundry Creditors		4,502 12 10
" Subscriptions received in advance		432 12 1
" Repairs Suspense Account :—		
Balance at 1st January, 1924	563 16 6	
Amount set aside in 1924	1,500 0 0	
	2,063 16 6	
Less Expenditure on Repairs in 1924	855 4 5	
		1,208 12 1
" Reserve Fund (Contingencies and Mortgage Redemption) :—		
Balance at 1st January, 1924	14,000 0 0	
Amount transferred to Reserve Fund in 1924	3,500 0 0	
		17,500 0 0
Carried Forward		38,339 9 6

ASSETS. **Cr.**

	£ s. d.	£ s. d.
By Institution Building and Lease :—		
Cost	73,028 6 10	
Less Reserve for Depreciation, being Surrender Values of Sinking Fund Policies	4,772 10 1	
		68,255 16 9
" Sinking Fund (Surrender Values of Policies for Redemption of Cost of Building and Lease)		4,772 10 1
" Tothill Street Buildings and Site (at cost)		19,260 17 1
" Kelvin Lecture Fund Investment (at cost)* :—		
£694 16s. 9d. 5 % War Stock (1929–47)		648 13 0
" Library (exclusive of the Ronalds Library and Faraday Papers, which are held in trust) :—		
As per last Balance Sheet	1,059 16 5	
Additions in 1924	323 15 11	
	1,383 12 4	
Less Depreciation (10 %)	138 7 3	
		1,245 5 1
" Thompson Memorial Library (Contribution towards purchase)		1,000 0 0
" Furniture, Fittings, and Apparatus :—		
As per last Balance Sheet	5,437 9 6	
Expenditure in 1924	391 0 3	
	5,828 9 9	
Less Depreciation (5 %)	291 8 6	
		5,537 1 3
" Sundry Debtors		4,179 1 9
" Insurance Premiums and Sundry Payments in Advance		724 14 3
" Stock of Paper, etc., for Publications		419 13 10
Carried Forward		106,043 13 1

BALANCE SHEET—*continued.*

Dr. LIABILITIES—*continued.*

		£ s. d.	£ s. d.
Brought Forward			38,339 9 6
To GENERAL FUND :—			
Balance at 1st January, 1924		110,750 10 0	
Obligatory Repayment to Economic Life Assurance Society		1,080 17 4	
Profit on Sale of £2,000 5½ % Exchequer Bonds		39 12 0	
Expenditure in 1924 on—			
Books and Binding for Library		323 15 11	
Furniture, Fittings and Apparatus		391 0 3	
Balance from Revenue Account for 1924 ...		2,925 0 8	
		115,510 16 2	
Less Depreciation :—			
Library (*per contra*)	£138 7 3		
Furniture, Fittings, and Apparatus (*per contra*)	291 8 6		
Museum (old instruments) ...	213 12 6		
		643 8 3	
			114,867 7 11
			£153,206 17 5

P. D. TUCKETT,
Honorary Treasurer.

P. F. ROWELL,
Secretary.

ASSETS—*continued.* **Cr.**

	£ s. d.	£ s. d.
Brought Forward		106,043 13 1
By GENERAL AND RESERVE FUNDS INVESTMENTS (at cost)* :—		
£2,600 Natal Zululand Railways 3 % Debenture Stock	2,270 12 0	
£1,500 London, Midland and Scottish Railway 4 % Preference Stock	1,513 10 4	
£2,000 Assam Bengal Railways 3 % Stock (1931 or after)	1,548 0 6	
£750 Western Australia 4 % Stock (1942–62) ...	730 8 3	
£750 Union of South Africa 4 % Stock (1943–63) ...	742 12 0	
£750 Madras and Southern Mahratta Railway 4 % Debenture Stock (1938)	738 15 6	
£35 East Indian Railway "B" Annuity (1953) ...	791 5 4	
£1,500 South Australia 4% Stock (1940–60)... ...	1,494 10 6	
£5,250 5 % War Stock (1929–47)	4,987 10 0	
£2,000 5 % National War Bonds (1929)	2,000 0 0	
£3,000 5 % National War Bonds (1928)	3,206 11 0	
£19,375 4 % Funding Loan (1960–90)	15,500 0 0	
£6,700 3½ % Conversion Stock (1961 or after) ...	5,054 14 3	
£5,000 5 % Treasury Bonds (1927)	5,084 15 6	
		45,663 5 2
„ CASH IN HANDS OF LOCAL CENTRES ON 30 SEPT., 1924		511 19 2
„ CASH :—		
At Bankers'	848 13 6	
In hands of Secretary	139 6 6	
		988 0 0
		£153,206 17 5

* The above values are subject to depreciation.

We beg to report that we have audited the Balance Sheet of The Institution of Electrical Engineers, dated 31st December, 1924, and above set forth, together with the annexed Statements of Account. We have obtained all the information and explanations we have required. In our opinion the Statements are correct, and the Balance Sheet is properly drawn up so as to exhibit a true and correct view of the state of the Institution's affairs according to the best of our information and the explanations given to us and as shown by the books of the Institution.

ALLEN, ATTFIELD & CO., *Auditors,*
Chartered Accountants,
24, MARTIN LANE, CANNON STREET, E.C. 4.

15th April, 1925.

SALOMONS SCHOLARSHIP TRUST FUND.

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	2,126 19 3	By Investments (at cost) :—	
" Bonus received on conversion of £1,500 New South Wales (1924) 3½ % Stock	28 15 7	£1,528 5s. 1d. New South Wales 5 % Stock (1935–55)	1,585 1 4
		£500 Cape of Good Hope 3½% Stock (1929–49)	570 13 6
	£2,155 14 10		£2,155 14 10

SALOMONS SCHOLARSHIP TRUST FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount paid to Scholars in 1924	87 10 0	By Balance (as per last Account)	48 5 0
" Balance carried to Balance Sheet *	33 7 4	" Dividends received in 1924	72 12 4
	£120 17 4		£120 17 4

DAVID HUGHES SCHOLARSHIP TRUST FUND.

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	2,000 0 0	By Investment (at cost) :—	
		£2,045 Staines Reservoirs 3% Guaranteed Debenture Stock (1922 or after)	1,998 15 0
		" Balance carried to Balance Sheet *	1 5 0
	£2,000 0 0		£2,000 0 0

DAVID HUGHES SCHOLARSHIP TRUST FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount paid to Scholars in 1924	87 10 0	By Balance (as per last Account)	58 8 4
" Balance carried to Balance Sheet *	31 19 4	" Dividends received in 1924	61 0 6
		" Interest do. do.	0 0 6
	£119 9 4		£119 9 4

PAUL SCHOLARSHIP FUND.

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	500 0 0	By Investment (at cost) :—	
		£625 4% Funding Loan (1960–90)	500 0 0
	£500 0 0		£500 0 0

PAUL SCHOLARSHIP FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Balance carried to Balance Sheet *	50 0 0	By Balance (as per last Account)	25 0 0
		" Dividends received in 1924	25 0 0
	£50 0 0		£50 0 0

* Included in the total of £325 17s. 6d. shown on the Liabilities side of the Balance Sheet

WILDE BENEVOLENT TRUST FUND.

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount (as per last Account)	2,798	10	2	By Investments (at cost) :—			
„ Amount transferred from Income in 1924 ...	150	16	5	£1,308 London and North Eastern Railway 4% First Guaranteed Stock	1,744	3	11
				£100 London County 3½% Consolidated Stock (1929 or after)	101	8	6
				£250 New South Wales 4% Stock (1942–62) ...	251	6	0
				£100 3½% War Stock (1925–28)	94	8	8
				£100 5% War Stock (1929–47)	95	0	0
				£381 15s. 1d. 4% Funding Loan (1960–90) ...	300	0	0
				£200 5% National War Bonds (1928)	211	11	0
				£200 Conversion Stock 3½% (1961 or after) ...	151	8	6
	£2,949	6	7		£2,949	6	7

WILDE BENEVOLENT TRUST FUND (Income).

Dr.	£	s.	d.	Cr.	£	s.	d.
To Grant made in 1924	30	0	0	By Balance (as per last Account)	182	9	7
„ Amount transferred to Capital in 1924 ...	150	16	5	„ Dividends received in 1924	105	7	6
„ Balance carried to Balance Sheet *	109	5	10	„ Interest do. do.	2	5	2
	£290	2	3		£290	2	3

WAR THANKSGIVING EDUCATION AND RESEARCH FUND (No. 1).

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount (as per last Account)	1,700	0	0	By Investment (at cost) :—			
				£2,000 5% War Stock (1929–47)...	1,700	0	0
	£1,700	0	0		£1,700	0	0

WAR THANKSGIVING EDUCATION AND RESEARCH FUND (No. 1) (Income).

Dr.	£	s.	d.	Cr.	£	s.	d.
To Grants made in 1924	100	0	0	By Balance (as per last Account)	100	0	0
„ Balance carried to Balance Sheet *	100	0	0	„ Dividends received in 1924	100	0	0
	£200	0	0		£200	0	0

* Included in the total of £325 17s. 6d. shown on the Liabilities side of the Balance Sheet.

THE BENEVOLENT FUND OF THE INSTITUTION OF ELECTRICAL ENGINEERS.

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR 1924.

Dr. — Expenditure.

	£ s. d.
To Grants	1,322 16 6
„ Printing, Stationery, Bank Charges, Postage, etc.	51 14 3
„ Unexpended Balance carried to Balance Sheet	266 9 11
	£1,641 0 8

Income. — Cr.

	£ s. d.
By Dividends on Investments	485 0 3
„ Interest	3 12 7
„ Annual Subscriptions	293 1 6
„ Donations of £5 and over	543 11 4
„ Donations under £5	315 15 0
	£1,641 0 8

BALANCE SHEET, 31ST DECEMBER, 1924.

Dr. — Liabilities.

		£ s. d.
To Capital Account:—		
As per last Balance Sheet		9,969 11 3
„ Income and Expenditure Account:—		
As per last Balance Sheet	£1,622 17 6	
Unexpended Balance in 1924	266 9 11	
		1,889 7 5
„ Sundry Creditors		50 10 0
		£11,909 8 8

Assets. — Cr.

		£ s. d.
By Investments (Capital), at cost:—		
£961 7s. 7d. Cape of Good Hope 3 % Stock (1933–43)		950 0 0
£593 1s. 7d. New South Wales 3 % Stock (1935)		600 0 0
£420 London and North Eastern Railway 4 % First Preference Stock		503 18 3
£450 London, Midland and Scottish Railway 4 % Debenture Stock		551 0 9
£750 East Indian Railway 3½ % Debenture Stock		737 18 0
£300 London, Midland and Scottish Railway 4 % Guaranteed Stock		333 11 6
£500 New Zealand 3½ % Stock (1940)		486 18 6
£500 Canada 3½ % Stock (1930–50)		478 16 0
£1,126 6s. 3d. 5 % War Stock (1929–47)		1,067 6 6
£350 New South Wales 4 % Stock (1942–62)		336 18 6
£200 3½ % War Stock (1925–28)		188 17 3
£2,128 8s. 6d. 4 % Funding Stock (1960–90)		1,624 2 0
£2,000 5 % National War Bonds (1928)		2,110 4 0
		9 969 11 3
„ Investments (Income) at cost:—		
£1,000 5 % War Stock (1929–47)	£1,002 19 3	
£665 3½ % Conversion Stock (1961)	501 14 0	
		1,504 13 3
„ Sundry Debtors		77 7 0
„ Cash:—		
At Bankers'	£320 5 1	
In hand	37 12 1	
		357 17 2
		£11,909 8 8

I have audited the above Balance Sheet and Income and Expenditure Account with the Books and Vouchers and certify them to be correct, and have verified the Investments with Certificates from Bankers. The Investments, which are stated at cost, are subject to depreciation.

15th April, 1925.

JAS. ATTFIELD, F.C.A.,
Honorary Auditor.

THE BENEVOLENT FUND.

27th ANNUAL GENERAL MEETING, 7 MAY, 1925.

(Held in the Institution Lecture Theatre.)

Mr. W. B. Woodhouse, President, took the chair at 5.30 p.m.

The notice convening the meeting was taken as read.

The minutes of the 26th Annual General Meeting held on the 8th May, 1924, were also taken as read and were confirmed and signed.

The Report of the Committee of Management (see below) and the Statement of Accounts for the year 1924 (see page 586) were presented and, on the motion of **The Chairman,** seconded by **Mr. P. Rosling,** were unanimously adopted.

On the motion of **Mr. Ll. B. Atkinson,** Mr. J. Attfield, F.C.A., was unanimously re-elected Hon. Auditor.

Mr. C. P. Sparks offered to make a donation to be invested to bring the invested capital which now stands at £9 969 11s. 3d. to £10 000. The offer was gratefully accepted by the Chairman.

Mr. F. B. O. Hawes advocated greater publicity of the Fund, with a view to increasing the Capital Account to meet the demands for pensions which the Fund will later be called upon to provide.

Mr. W. T. Maccall, Chairman of the North-Eastern Centre, suggested that the other Local Centres might mention the Benevolent Fund in their Annual Reports in the same way as the North-Eastern Centre.

The Chairman reported that the following Committee of Management had been appointed for 1925–26:—

The President (*ex officio*); Sir James Devonshire, K.B.E., Captain J. M. Donaldson, M.C., Sir B. Longbottom, Mr. S. W. Melsom, Mr. A. Page and Mr. P. Rosling, representing the Council; Lieut.-Col. K. Edgcumbe, Mr. W. R. Rawlings and Captain R. J. Wallis-Jones, representing the Contributors; and the Chairman of each Local Centre in Great Britain and Ireland.

The meeting then terminated.

REPORT OF THE COMMITTEE OF MANAGEMENT FOR THE YEAR 1924.

Capital.

The Capital Account stood on the 31st December, 1924, at £9 969 11s. 3d., which is invested.

Receipts.

The Income for 1924 from dividends, interest, and annual subscriptions was as follows :—

	£	s.	d.
Dividends on investments	485	0	3
Interest	3	12	7
327 annual subscriptions	293	1	6
	£781	14	4

In addition to the foregoing, the Fund benefited during the year by the following amounts, many of which are non-recurring donations

	£	s.	d.
Electrical Engineers' Ball Committee	75	0	0
Electrical Standardizing, Testing and Training Institution	50	0	0
"Gilbert Club"	40	5	11
Western Electric Co., Ltd.	40	0	0
Wembley Exhibition Carnival	38	12	4
North Midland Centre (collected)	26	17	0
C. P. Sparks, C.B.E.	26	5	0
W. T. Henley's Telegraph Works, Ltd.	25	0	0
Western Centre (collected)	21	14	11
General Electric Co., Ltd.	21	0	0
H. Marryat	21	0	0
Midland Electrical Engineers' Ball Committee	21	0	0
"Twenty-Five" Club	15	15	0
Chloride Electrical Storage Co., Ltd.	10	10	0
H. Hirst	10	10	0
Incorporated Municipal Electrical Association	10	10	0
F. R. Marsh	10	10	0
J. D. Dallas	10	0	0
and 694 non-recurring donations of under £10	361	1	2
	£809	6	4

The Fund also benefited to the extent of £50 under the will of the late Mr. A. L. Dearlove (Member).

The accumulated balance of the Income and Expenditure Account amounted on the 31st December, 1924, to £1 889 7s. 5d., of which £1 504 13s. 3d. was invested, and £225 on deposit with the Institution bankers.

Donors and Subscribers.

Lists of the names of donors and subscribers during 1924 have been published in the *Journal*.

The Committee of Management desire to acknowledge their indebtedness to the donors and subscribers, and to intimate that, apart from donations, the Committee will be grateful for annual subscriptions of any amount.

Grants.

Applications for assistance were made by or on behalf of 26 persons during 1924, and the Committee, after due consideration, made grants in all of the cases. The total amount of the grants was £1 322 16s. 6d.

Wilde Fund.

The Capital Account stood on the 31st December, 1924, at £2 949 6s. 7d., all of which is invested and brings in an annual income of £106 11s. 10d.

The balance standing to the credit of the Income Account, from which, under the Trust Deed, full Members only can benefit, on the same date was £109 5s. 10d.

A grant of £30 was made from this Fund during the year,

WAVE-FORM ANALYSIS ON RECTIFIED CIRCUITS.*

By L. B. W. JOLLEY, M.A., Member.

(*Paper received 2nd January, 1925.*)

SUMMARY.

This paper analyses the form of various waves to be expected in rectified circuits, and by the general method of treatment the analysis could be applied to a pronounced commutator ripple. A specialized form of wave-form, due to a rectifier where a sharp cut-off of the current is to be expected, is also considered.

The use of rectified alternating current is becoming daily more common, and a knowledge of the wave-form of the resulting direct current is essential for the user and designer alike. Accordingly an attempt has been made to analyse the various forms most likely to be encountered in practice; and although these curves are ideal and will be more or less distorted in actuality, yet they represent facts to a reasonable degree of accuracy, or at least give an indication as to what harmonics are likely to be present.

SINGLE-PHASE WAVE-FORM.

The first case considered is that of a single-phase wave-form as shown in Fig. 1 (*b*), resulting from the

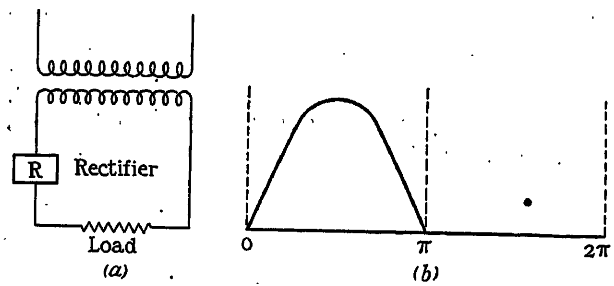


FIG. 1.

circuit indicated in Fig. 1 (*a*), where the shape of the curve is given by the equation $y = \sin\theta$.

If the function is represented by a Fourier's series

$$y = \tfrac{1}{2}a_0 + a_1\cos\theta + a_2\cos 2\theta + \ldots \infty$$
$$+ b_1\cos\theta + b_2\cos 2\theta + \ldots \infty$$

then

$$a_n = \frac{1}{\pi}\int_0^{\pi}\sin\theta\cos n\theta\,d\theta$$

and

$$b_n = \frac{1}{\pi}\int_0^{\pi}\sin\theta\sin n\theta\,d\theta$$

whence

$$a_n = \frac{1+\cos n\pi}{\pi(1-n^2)}$$

and

$$b_n = \frac{\sin n\pi}{\pi(1-n^2)}$$

Thus b_n is zero for all integral values of n except unity, where it equals $\tfrac{1}{2}$.

The wave-form is therefore

$$y = \frac{1}{\pi} + \tfrac{1}{2}\sin\theta - \frac{2\cos 2\theta}{\pi(1.3)} - \frac{2\cos 4\theta}{\pi(3.5)} - \ldots \infty \quad (1)$$

$$= \frac{1}{\pi} + \tfrac{1}{2}\sin\theta - \frac{2}{\pi}\sum_2^{\infty}\frac{\cos^2\tfrac{1}{2}n\pi\cos n\theta}{n^2-1} \quad . \quad . \quad . \quad (2)$$

BIPHASE WAVE-FORM.

From Equation (2) the biphase wave-form, which is obtained from the circuit illustrated in Fig. 2 (*a*), can be calculated and will be of the form shown in Fig. 2 (*b*).

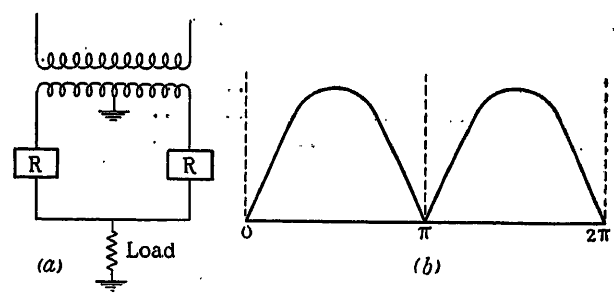


FIG. 2.

In this case let us write $\theta = \pi + \theta$ in Equation (2), whence

$$y = \frac{1}{\pi} - \tfrac{1}{2}\sin\theta - \frac{2}{\pi}\sum_2^{\infty}\frac{\cos^2\tfrac{1}{2}n\pi\cos n\theta}{n^2-1} \quad . \quad (3)$$

and by adding Equations (2) and (3)

$$y = \frac{2}{\pi}\left[1 - 2\sum_2^{\infty}\frac{\cos^2\tfrac{1}{2}n\pi\cos n\theta}{n^2-1}\right] \quad . \quad . \quad (4)$$

is obtained for the equation of a biphase wave. Thus it will be apparent that in this wave-formation the fundamental is absent and only even harmonics are present.

POLYPHASE WAVE-FORM.

It is interesting to investigate the general case of a multiphase system, and in Fig. 3 circuit connections

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are given for a hexaphase supply, the method being of general application. The wave-form of such a supply is shown in Fig. 4, and if there are m phases there will be m complete loops in one cycle or 2π electrical degrees, the crest of the loop strictly following the sinusoidal curvature. The equation to the generating curve is in this case $y = \cos\theta$.

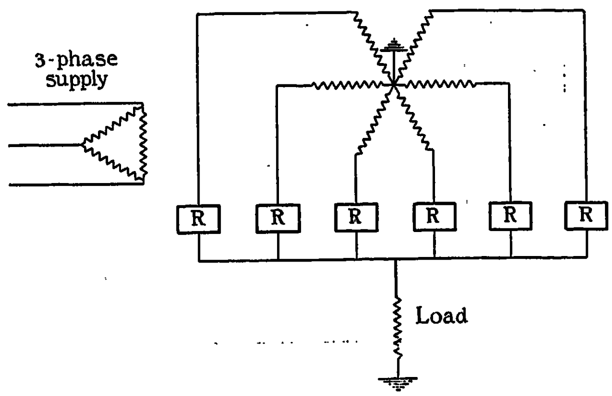

FIG. 3.

It is shown in treatises dealing with Fourier's series that the amplitudes of the nth harmonics between limits other than $\pm\pi$ can be obtained as follows :—

Assume the series to be

$$f(\theta) = \tfrac{1}{2}a_0 + a_1\cos(\pi\theta/c) + a_2\cos(2\pi\theta/c) + \ldots \infty$$
$$+ b_1\cos(\pi\theta/c) + b_2\cos(2\pi\theta/c) + \ldots \infty$$

Then $$a_n = \frac{2}{c}\int_0^c f(\theta)\cos\left(\frac{n\pi\theta}{c}\right)d\theta$$

and $$b_n = \frac{2}{c}\int_0^c f(\theta)\sin\left(\frac{n\pi\theta}{c}\right)d\theta$$

or $$a_n = \frac{1}{c}\int_{-c}^{+c} f(\theta)\cos\left(\frac{n\pi\theta}{c}\right)d\theta$$

and $$b_n = \frac{1}{c}\int_{-c}^{+c} f(\theta)\sin\left(\frac{n\pi\theta}{c}\right)d\theta$$

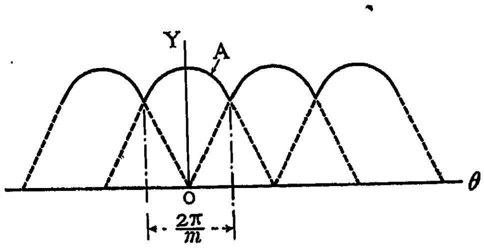

FIG. 4.

In this case $c = \pi/m$ and $n\pi\theta/c = nm\theta$, whence

$$\frac{\pi a_n}{m} = \int_{-\pi/m}^{+\pi/m}\cos\theta\cos(nm\theta)d\theta$$

and $$a_n = \frac{2m\sin(\pi/m)\cos n\pi}{\pi(1 - n^2m^2)} \quad . \quad . \quad . \quad (5)$$

Further $$\frac{\pi b_n}{m} = \int_{-\pi/m}^{+\pi/m}\cos\theta\sin(nm\theta)d\theta = 0$$

and all the sine terms are absent (this statement requires modification where $m = 1$, the single-phase wave-form considered above).

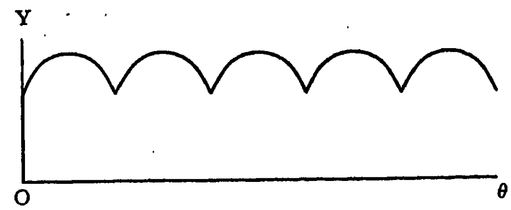

FIG. 5.

The general equation of the wave-form is therefore

$$\frac{m}{\pi}\sin\frac{\pi}{m} - \frac{2m\sin(\pi/m)\cos m\theta}{\pi(1 - m^2)}$$
$$+ \frac{2m\sin(\pi/m)\cos 2m\theta}{\pi(1 - 2^2m^2)} - \ldots \infty \quad (6)$$

$$= \frac{m}{\pi}\sin\frac{m}{\pi}\left[1 + 2\sum_{n=1}^{\infty}\frac{\cos n\pi\cos nm\theta}{1 - n^2m^2}\right] \quad . \quad (7)$$

If it is desired to reproduce the wave-form to a different set of co-ordinates, as shown in Fig. 5, it is necessary to substitute $(\theta - \pi/m)$ for θ in Equation (7), which then becomes

$$\frac{m}{\pi}\sin\frac{\pi}{m}\left[1 - \frac{2\cos m\theta}{m^2 - 1} - \frac{2\cos 2m\theta}{4m^2 - 1} - \ldots \infty\right] \quad . \quad (8)$$

$$= \frac{m}{\pi}\sin\frac{\pi}{m}\left[1 + 2\sum_{1}^{\infty}\frac{\cos nm\theta}{1 - n^2m^2}\right] \quad . \quad . \quad (9)$$

in which form it is more convenient. In future, and in the table below, this equation will be used.

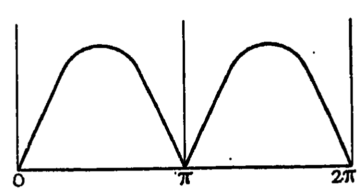

FIG. 6.

It is interesting to apply a check to this result, and to this end an infinite series is employed of the form

$$\frac{m}{\pi}\operatorname{cosec}\frac{\pi}{m} = 1 + 2\sum_{1}^{\infty}\frac{(-1)^n}{1 - n^2m^2}$$

If the midpoint of the oscillations is considered, i.e. the point represented by $\theta = \pi/m$, the amplitudes of the harmonics all have a maximum value, and hence

Equation (9) equals unity, which is the peak value of the wave.

If m is given the values 2, 3, 4, etc., to represent the number of phases or loops per cycle, the following wave-forms are obtained :—

m = 2 (*Biphase*) Fig. 6.

$$\frac{2}{\pi} - \frac{4\cos 2\theta}{\pi(1.3)} - \frac{4\cos 4\theta}{\pi(3.5)} - \ldots \infty$$

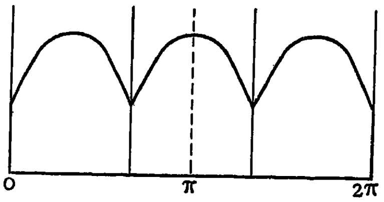

FIG. 7.

m = 3 (*Triphase*) Fig. 7.

$$\frac{3\sqrt{3}}{2\pi} - \frac{3\sqrt{3}\cos 3\theta}{\pi(2.4)} - \frac{3\sqrt{3}\cos 6\theta}{\pi(5.7)} - \ldots \infty$$

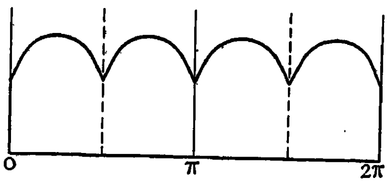

FIG. 8.

m = 4 (*Quarter Phase*) Fig. 8.

$$\frac{2\sqrt{2}}{\pi} - \frac{4\sqrt{2}\cos 4\theta}{\pi(3.5)} - \frac{4\sqrt{2}\cos 8\theta}{\pi(7.9)} - \ldots \infty$$

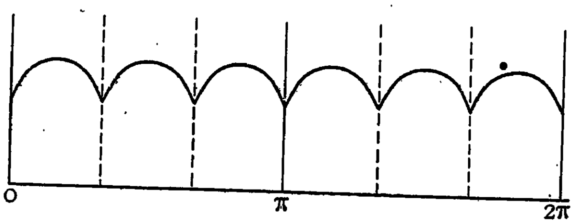

FIG. 9.

m = 6 (*Hexaphase*) Fig. 9.

$$\frac{3}{\pi} - \frac{6\cos 6\theta}{\pi(5.7)} - \frac{6\cos 12\theta}{\pi(11.13)} - \ldots \infty$$

m = 18 (*Eighteen Phase*).

$$0{\cdot}999\left[1 - \frac{2\cos 18\theta}{17.19} - \frac{2\cos 36\theta}{35.37} - \ldots \infty\right]$$

With regard to the mean square value of the wave, this will be equal to

$$\mathfrak{J}^2 = \frac{m^2}{\pi^2}\sin^2\frac{\pi}{m}\left[1 + 2\sum_1^{\infty}\frac{1}{(1-n^2m^2)^2}\right]$$

TABLE.—*Polyphase Wave-Form Data.*

Number of phases	R.M.S. value $\mathfrak{J}$	Mean value I_M	Form factor	Amplitude of nth harmonic	Maximum value ÷ R.M.S.	Maximum value ÷ mean	Minimum ordinate	Area under one loop
m	$\sqrt{\left(\frac{1}{2}+\frac{m}{4\pi}\sin\frac{2\pi}{m}\right)}$	$\frac{\pi}{m}\sin\frac{\pi}{m}$	$\frac{\mathfrak{J}}{I_M}$	$\frac{2m\sin(\pi/m)}{\pi(1-n^2m^2)}$	$\frac{1}{\mathfrak{J}}$	$\frac{\pi}{m}\operatorname{cosec}\frac{\pi}{m}$	$\cos\frac{\pi}{m}$	$\int_{\frac{1}{2}\pi-\pi/m}^{\frac{1}{2}\pi+\pi/m}\sin\theta d\theta$
1	$\frac{1}{2} = 0{\cdot}500$	$1/\pi = 0{\cdot}318$	$\frac{1}{2}\pi = 1{\cdot}570$	$\frac{2}{\pi(1-4n^2)}$	2	$\pi = 3{\cdot}141$	0	2
2	$1/\sqrt{2} = 0{\cdot}707$	$2/\pi = 0{\cdot}636$	$\frac{\pi}{2\sqrt{2}} = 1{\cdot}110$	$\frac{4}{\pi(1-4n^2)}$	$\sqrt{2} = 1{\cdot}414$	$\frac{1}{2}\pi = 1{\cdot}570$	0	2
3	0·840	0·825	1·02	$\frac{3\sqrt{3}}{\pi(1-9n^2)}$	1·19	1·210	0·500	0·866
4	0·905	0·904	1·005	$\frac{8}{\pi\sqrt{2}(1-16n^2)}$	1·105	1·105	0·707	0·717
6	0·956	0·955	1·005	$\frac{6}{\pi(1-36n^2)}$	1·045	1·045	0·866	0·500
12	0·989	0·989	1·00	$\frac{24\sin 15^\circ}{\pi(1-144n^2)}$	1·01	1·01	0·966	0·342
18	0·995	0·995	1·00	$\frac{36\sin 10^\circ}{\pi(1-324n^2)}$	1·005	1·005	0·985	0·174

To sum the series $\sum_{1}^{\infty} \frac{1}{(1-n^2m^2)^2}$ two infinite series are employed, viz.

$$\pi \cot \pi\theta = \frac{1}{\theta} + \sum_{1}^{\infty} \frac{2\theta}{\theta^2 - n^2}$$

and $$\pi^2 \operatorname{cosec}^2 \pi\theta = \frac{1}{\theta^2} + 2\sum_{1}^{\infty} \frac{\theta^2 + n^2}{(\theta^2 - n^2)^2}$$

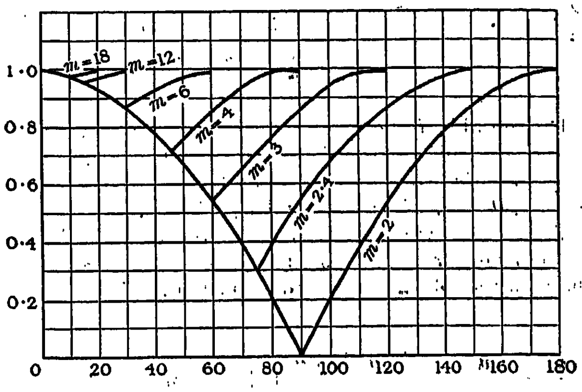

FIG. 10.

Whence, putting $\theta = 1/m$,

$$\sum_{n=1}^{\infty} \frac{1}{(1-n^2m^2)^2} = \left(\frac{\pi}{2m} \operatorname{cosec} \frac{\pi}{m}\right)^2 + \frac{\pi}{4m} \cot \frac{\pi}{m} - \frac{1}{2}$$

and therefore

$$\mathfrak{J}^2 = \frac{1}{2} + \frac{m}{4\pi} \sin \frac{2\pi}{m}$$

This result could also have been obtained directly by evaluating

$$\frac{m}{2\pi}\int_{\frac{1}{2}\pi - \pi/m}^{\frac{1}{2}\pi + \pi/m} \sin^2 \theta d\theta$$

The actual wave-forms to scale are indicated in Fig. 10, and show how the form factor is improved by increasing the number of phases.

From the above analysis, the table shown on page 590 can be prepared.

SPECIAL WAVE-FORMS.

In some forms of rectifier, such, for instance, as the vibrating reed or the neon tube, the voltage rises to a certain value before the current flows, and the current

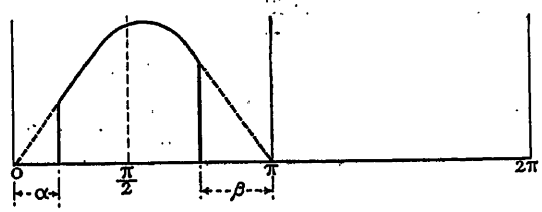

FIG. 11.

is cut off before the voltage has fallen to zero. Such an oscillation will take the form of Fig. 11, where the form of the generating curve is $y = \sin \theta$. From Fourier's series the amplitudes of the nth harmonics are

$$a_n = \frac{1}{\pi}\int_{\alpha}^{\pi-\beta} \sin \theta \cos n\theta \, d\theta$$

and $$b_n = \frac{1}{\pi}\int_{\alpha}^{\pi-\beta} \sin \theta \cos n\theta \, d\theta$$

whence

$$a_n = \frac{\cos n\pi\{\cos \beta \cos n\beta + n \sin \beta \sin n\beta\} + \cos \alpha \cos n\alpha + n \sin \alpha \sin n\alpha}{\pi(1-n^2)}$$

and $$b_n = \frac{\cos n\pi\{n \sin \beta \cos n\beta - \cos \beta \sin n\beta\} + \cos \alpha \sin n\alpha - n \sin \alpha \cos n\alpha}{\pi(1-n^2)}$$

from which $\frac{1}{2}a_0 = \frac{\cos \alpha + \cos \beta}{2\pi}$.

Similarly, by differentiating the numerator and denominator of a_n and b_n and putting $n = 1$

$$a_1 = \frac{\sin^2 \beta - \sin^2 \alpha}{2\pi}$$

and $$b_1 = \frac{\sin \alpha \cos \alpha + \sin \beta \cos \beta - \alpha - \beta + \pi}{2\pi}$$

The complete expression of the wave-form then becomes

$$y = \frac{\cos \alpha + \cos \beta}{2\pi} + \left(\frac{\sin \alpha \cos \alpha + \sin \beta \cos \beta - \alpha - \beta + \pi}{2\pi}\right) \sin \theta + \left(\frac{\sin^2 \beta - \sin^2 \alpha}{2\pi}\right) \cos \theta$$

$$- \sum_{2}^{\infty} \frac{\cos n\pi\{\cos \beta \cos n\beta + n \sin \beta \sin n\beta\} + \cos \alpha \cos n\alpha + n \sin \alpha \sin n\alpha}{\pi(n^2 - 1)} \cos n\theta$$

$$- \sum_{2}^{\infty} \frac{\cos n\pi\{n \sin \beta \cos n\beta - \cos \beta \sin n\beta\} + \cos \alpha \sin n\alpha - n \sin \alpha \cos n\alpha}{\pi(n^2 - 1)} \sin n\theta \quad . \quad (10)$$

The following series are useful in computing R.M.S. and average values :—

$$\sum_{2}^{\infty}\frac{\cos n\pi\cos n\theta}{n^2-1}=\frac{\cos 2\theta}{1.3}-\frac{\cos 3\theta}{2.4}+\ldots\infty$$
$$=\tfrac{1}{2}-\tfrac{1}{4}\cos\theta-\tfrac{1}{2}\theta\sin\theta$$

$$\sum_{2}^{\infty}\frac{\cos n\pi(n\sin n\theta)}{n^2-1}=\frac{2\sin 2\theta}{1.3}-\frac{3\sin 3\theta}{2.4}+\ldots\infty$$
$$=\tfrac{1}{2}\theta\cos\theta+\tfrac{1}{4}\sin\theta$$

$$\sum_{2}^{\infty}\frac{\cos n\theta}{n^2-1}=\frac{\cos 2\theta}{1.3}+\frac{\cos 3\theta}{2.4}+\ldots\infty$$
$$=\tfrac{1}{2}+\tfrac{1}{4}\cos\theta-\tfrac{1}{2}\pi\sin\theta+\tfrac{1}{2}\theta\sin\theta$$

$$\sum_{2}^{\infty}\frac{n\sin\theta}{n^2-1}=\frac{2\sin 2\theta}{1.3}+\frac{3\sin 3\theta}{2.4}+\ldots\infty$$
$$=\tfrac{1}{2}\pi\cos\theta-\tfrac{1}{4}\sin\theta-\tfrac{1}{2}\theta\cos\theta$$

$$\sum_{2}^{\infty}\frac{\cos\frac{1}{2}n\pi\cos n\theta}{n^2-1}=-\frac{\cos 2\theta}{1.3}+\frac{\cos 4\theta}{3.5}-\ldots\infty$$
$$=\tfrac{1}{2}-\tfrac{1}{4}\pi\cos\theta$$

$$\sum_{2}^{\infty}\frac{\cos\frac{1}{2}n\pi(n\sin\theta)}{n^2-1}=-\frac{2\sin 2\theta}{1.3}+\frac{4\sin 4\theta}{3.5}-\ldots\infty$$
$$=-\tfrac{1}{4}\pi\sin\theta$$

$$\sum_{2}^{\infty}\frac{\sin\frac{1}{2}n\pi\sin n\theta}{n^2-1}=-\frac{\sin 3\theta}{2.4}+\frac{\sin 5\theta}{4.6}-\ldots\infty$$
$$=\tfrac{1}{4}\sin\theta-\tfrac{1}{2}\theta\cos\theta$$

$$\sum_{2}^{\infty}\frac{\sin\frac{1}{2}n\pi(n\cos n\theta)}{n^2-1}=-\frac{3\cos 3\theta}{2.4}+\frac{5\cos 5\theta}{4.6}-\ldots\infty$$
$$=-\tfrac{1}{4}\cos\theta+\tfrac{1}{2}\theta\sin\theta$$

By the aid of these series it is possible to check the above generalized formulæ by putting $\theta=\frac{1}{2}\pi$, in which case the whole expression should equal unity; or by putting $\theta=0$, when it should equal zero.

The biphase wave-form as shown in Fig. 12 is obtained by replacing $\pi+\theta$ for θ in Equation (10) and adding the result so obtained to Equation (10). Thus

$$y=\frac{\cos\alpha+\cos\beta}{2\pi}-\sum_{2}^{\infty}\frac{\cos\beta\cos n\beta+n\sin\beta\sin n\beta+\cos\alpha\cos n\alpha+n\sin\alpha\sin n\alpha}{\pi(n^2-1)}(1+\cos n\pi)\cos n\theta$$
$$-\sum_{2}^{\infty}\frac{n\sin\beta\cos n\beta-\cos\beta\sin n\beta+\cos\alpha\sin n\alpha-n\sin\alpha\cos n\alpha}{\pi(n^2-1)}(1+\cos n\pi)\sin n\theta \quad . \quad . \quad . \quad . \quad (11)$$

If $\alpha=\beta$, i.e. the point of cut-off is equal to the point of cut-in, or the current wave is symmetrical, the following relationships obtain :—

Single-Phase (Fig. 11).

$$y=\frac{\cos\alpha}{\pi}+\frac{\sin 2\alpha-2\alpha+\pi}{2\pi}\sin\theta$$
$$-\sum_{2}^{\infty}\frac{\cos\alpha\cos n\alpha+n\sin\alpha\sin n\alpha}{\pi(n^2-1)}\times(1+\cos n\pi)\cos n\theta$$
$$-\sum_{2}^{\infty}\frac{n\sin\alpha\cos n\alpha-\cos\alpha\sin n\alpha}{\pi(n^2-1)}\times(\cos n\pi-1)\sin n\theta \quad . \quad (12)$$

and the fundamental cosine term disappears.

Biphase (Fig. 12).

$$y=\frac{2\cos\alpha}{\pi}-2\sum_{2}^{\infty}\frac{\cos\alpha\cos n\alpha+n\sin\alpha\sin n\alpha}{\pi(n^2-1)}\times(1+\cos n\pi)\cos n\theta \quad . \quad (13)$$

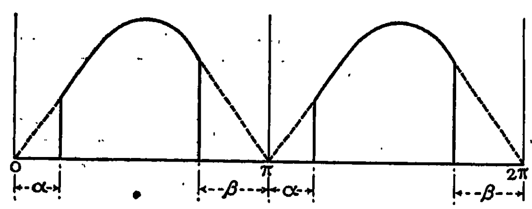

FIG. 12.

and both fundamental terms vanish as well as all of the sine terms.

SOME ARTIFICIAL LINES AND NETWORKS ASSOCIATED WITH THE UNIFORM TELEPHONE TRANSMISSION LINE.*

By the RESEARCH STAFF OF THE GENERAL ELECTRIC CO., LTD.

(Work conducted by A. C. BARTLETT.)

(*Paper first received* 21*st November*, 1924, *and in final form* 14*th January*, 1925.)

SUMMARY.

In Part 1 it is shown that the problem of constructing a network the impedance of which shall be equal to the impedance of an infinite uniform telephone line, can be solved exactly by the use of a number of sections of simple artificial lines. The artificial lines described are intended entirely for use in this way, and since their propagation constants are widely different from that of the uniform line, they cannot be used as "artificial transmission lines" to which any terminal apparatus might be added.

Some of the artificial lines can be used for attenuation correction.

In Part 2 it is shown that related networks can be obtained such that when placed in series or in parallel with the infinite uniform line, the impedance of the combination is a pure resistance.

Part 1.

It is often necessary for laboratory purposes and for use in telephonic work—especially where telephone repeaters are used—to obtain networks the input impedance/frequency characteristics of which will be

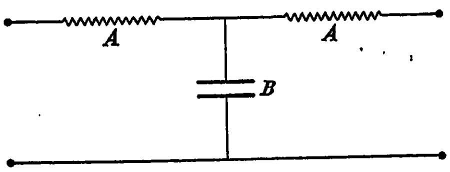

FIG. 1.

the same as those of an infinite, uniform, telephone transmission line.

A number of approximate solutions are known which make use of networks of resistances and condensers.†

It is the purpose of this paper to show that, by the use of simple artificial lines,‡ the impedance elements of which can be calculated from the constants of the line, a precise solution of this problem may be obtained.

The impedance of an infinite uniform line is $\sqrt{[(R + jpL)/(S + jpC)]}$ where R, L, C and S are the resistance, inductance, capacity and leakage per unit length.

The characteristic impedance of a **T**-section artificial line is $\sqrt{(A^2 + 2AB)}$, where A is the series member and B the shunt member. It is interesting to consider whether $(R + jpL)/(S + jpC)$ can be put in the form of $A^2 + 2AB$ with A and B both physically realizable.

Take first the simple case where $S = 0$. We have

$$\frac{R + jpL}{jpC} = \frac{L}{C}\left(1 + \frac{R}{jpL}\right)$$
$$= \left(\sqrt{\frac{L}{C}}\right)^2 + 2\left(\sqrt{\frac{L}{C}}\right)\frac{R}{2jp\sqrt{(LC)}}$$

But $\sqrt{(L/C)}$ is of the dimensions of a resistance, and $\sqrt{(LC)}/R$ is of the dimensions of a capacity.

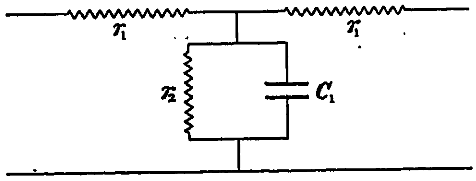

FIG. 2.

Hence the simple **T** section of Fig. 1, where A is a resistance $\sqrt{(L/C)}$, and B a capacity $2\sqrt{(LC)}/R$, has a line characteristic impedance equal to

$$\sqrt{[(R + jpL)/jpC]}.$$

The impedance of n sections of the line is

$$\sqrt{[(R + jpL)/jpC]} \tanh n\theta$$

or
$$\sqrt{[(R + jpL)/jpC]} \coth n\theta,$$

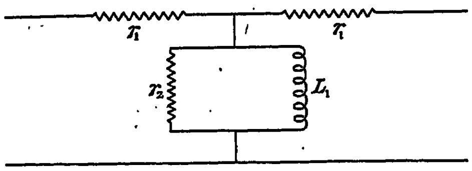

FIG. 3.

according as they are closed or open-circuited at the far end, where $\cosh \theta = 1 + A/B$. Tanh $n\theta$ and coth $n\theta$ approach the value unity at all frequencies as n is increased. Accordingly an impedance approximating as closely as desired to $\sqrt{[(R + jpL)/jpC]}$ can be obtained by using sufficient sections.

In practice for aerial telephone lines two or three sections give an approximation within 1 or 2 per cent for all frequencies above 200 cycles per second.

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† HOYT: *Bell System Technical Journal*, April 1923.

‡ For general theory of artificial lines see KENNELLY: "Artificial Electric Lines" [McGraw-Hill].

Similar results hold when $S \neq 0$.

When $RC > LS$ we have the section given in Fig. 2,

where
$$r_1 = \sqrt{(L/C)}$$
$$r_2 = \tfrac{1}{2}\left(\sqrt{\frac{L}{C}}\right)\left(\frac{RC}{LS} - 1\right)$$
$$C_1 = 2C\frac{\sqrt{(LC)}}{RC - LS}$$

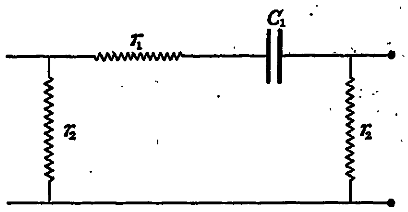

FIG. 4.

When $RC < LS_1$ we have the section given in Fig. 3,

where
$$r_1 = \sqrt{(R/S)},$$
$$r_2 = \tfrac{1}{2}\left(\sqrt{\frac{R}{S}}\right)\left(\frac{LS}{RC} - 1\right)$$
$$L_1 = \tfrac{1}{2}\left(\sqrt{\frac{1}{RS}}\right)\left(\frac{LS - RC}{S}\right)$$

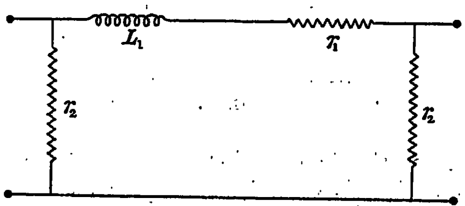

FIG. 5.

In a similar manner Π sections can be obtained. There are three cases, viz.

$$RC > LS;\ S \neq 0$$
$$RC < LS,$$
and
$$S = 0.$$

Case 1. $RC > LS$. $S \neq 0$ (see Fig. 4). We have

$$r_1 = \left(\sqrt{\frac{S}{R}}\right)\left(\frac{RL}{CR - LS}\right)$$
$$r_2 = \sqrt{(R/S)}$$
$$C_1 = \frac{CR - LS}{SR}\sqrt{\frac{S}{R}}$$

Case 2. $RC < LS$ (see Fig. 5). We have

$$r_1 = \left(\sqrt{\frac{L}{C}}\right)\left(\frac{CR}{LS - CR}\right)$$
$$r_2 = \sqrt{(L/C)}$$
$$L_1 = \frac{2\sqrt{(LC)}}{LS - CR}$$

Case 3. $S = 0$ (see Fig. 6). We have

$$r_1 = 2\sqrt{(L/C)}$$
$$L_1 = (2L/R)\sqrt{(L/C)}$$
$$r_2 = \sqrt{(L/C)}$$
$$C_1 = \frac{\sqrt{(LC)}}{R}$$

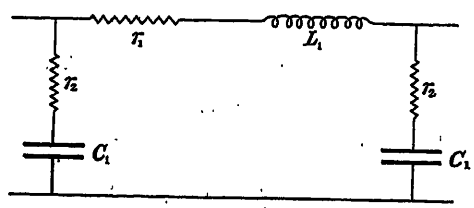

FIG. 6.

It may be noticed that the Π and **T** sections for any one case have the same propagation constant, and are thus exactly equivalent. An interesting way of deriving one from the other is to reciprocate one infinite line of **T** sections with respect to itself (i.e. with respect to

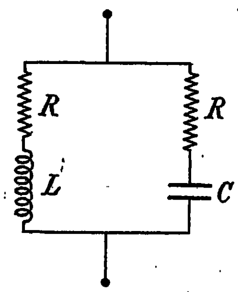

FIG. 7.

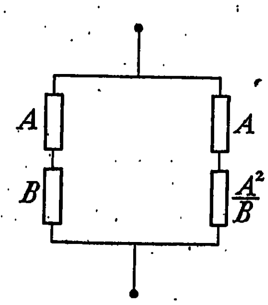

FIG. 8.

its line characteristic impedance) when the corresponding infinite line of Π sections is obtained, and vice versa.

Bridge-type artificial lines having the same impedance as uniform lines can also be obtained. Here it is necessary to express $(R + jpL)/(S + jpC)$ in the form $A \times B$. One obvious way is $x(R + jpL)[1/x(S + jpC)]$. x may be any numerical quantity and may be chosen so that the attenuation constant is a maximum within any range of frequencies that may be desired.

The attenuation constant α, which is the real part of the propagation constant, can be calculated and it will be found generally that, for any value of x, α will have a maximum at one frequency. From this it follows that by using suitable values of x, artificial lines can be obtained whose attenuation constant decreases with increasing frequency over a certain frequency range. Such a section, or number of such sections, may be inserted in a uniform line and used to compensate for the increase with frequency of the attenuation constant of the uniform line. Also, since the line characteristic impedance of the artificial line is the same as that of the uniform line, no reflection or impedance disturbance is introduced.

Other bridge types may be derived from the **T** sections

just given by using bridge arms such as xA and $(1/x)(A + 2B)$.

By terminating n sections of any of these artificial lines by $Z_0 \tanh \frac{1}{2}\theta$ the impedance $Z_0 \tanh \frac{1}{2}(2n + 1)\theta$ is obtained, and by terminating by $Z_0 \coth \frac{1}{2}\theta$ the impedance $Z_0 \coth \frac{1}{2}(2n + 1)\theta$ is obtained. Hence two series of approximations to Z_0 can be obtained of which the first five members for a **T** section are shown in Fig. 16.

Having decided on a definite number of sections, any of the equivalent networks obtainable by the methods previously given * can be substituted.

As a practical example consider the case of a 200-lb. copper air line having the following constants per mile :—

$$R = 8{\cdot}8 \text{ ohms.}$$
$$S = 10^{-6} \text{ mho.}$$
$$C = 8{\cdot}6 \times 10^{-9}\ \mu\text{F.}$$
$$L = 3{\cdot}66 \times 10^{-3}\ \text{H.}$$

cycles per second, and the results are shown in vector form in Table 1.

TABLE 1.

	$p = 2\,000$ (300 ~ approx.)	$p = 12\,000$ (2 000 ~ approx.)
Tanh θ	1·06 /5° 24′	1·0045 /3′
Tanh 2θ	1·0034 /19′	0·99913 /0·86″
Tanh 3θ	0·9996 /5″	Very nearly unity
Tanh 6θ	0·999999 /0·004″	Very nearly unity

It will be seen that a high degree of approximation is very soon attained and that two or three sections give

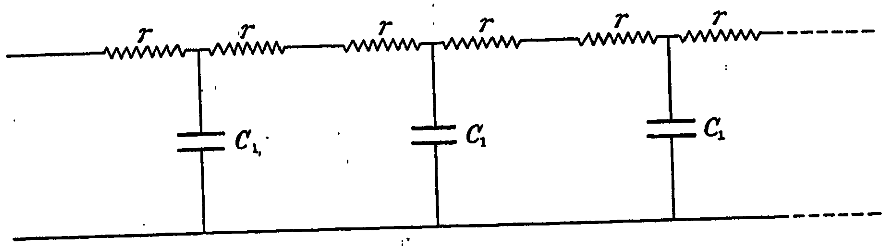

FIG. 9.

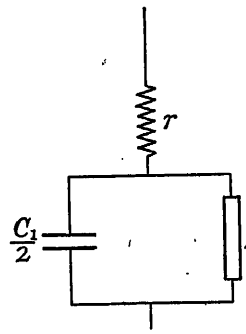

FIG. 10.

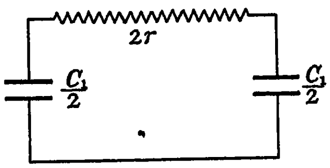

FIG. 11.

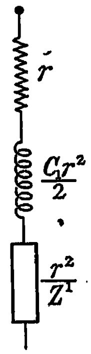

FIG. 12.

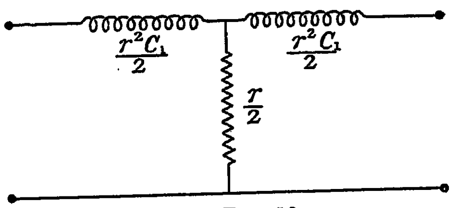

FIG. 13.

A line balance can be made using **T** sections such as that shown in Fig. 2,

where
$$r_1 = 652 \text{ ohms}$$
$$r_2 = 6\,420 \text{ ohms}$$
$$C_1 = 1{\cdot}34\ \mu\text{F}$$

If n sections are used, short-circuited at the far end, the ratio of the impedance of this network to that of the given uniform line will be $\tanh n\theta$. Tanh $n\theta$ has been calculated for this case for $n = 1$, 2, 3 and 6, and $p = 2\,000$ and $12\,000$, i.e. for about 300 and 2 000

* *Philosophical Magazine*, 1925, vol. 49, p. 728.

an accuracy much greater than is usually required in practice.

Part 2.

It is well known that the impedance of the network shown in Fig. 7 is equal to R, provided that $L = R^2C$, i.e. $jpL = R^2/(1/jpC)$, or the impedances of L and C are reciprocal to R. This at once suggests the generalization that the impedance of the circuit of Fig. 8 is identically equal to A ; the proof is obvious. If A is resistance, the reciprocals of a resistance, a capacity or an inductance with respect to A are a resistance, an inductance or a capacity respectively. Now we know that the

impedance of a uniform line (assumed to be without leakage for the sake of simplicity) can be represented by a network of the form of Fig. 9. This is of the form of Fig. 10, where Z' is the infinite Π-section artificial line having the section shown in Fig. 11.

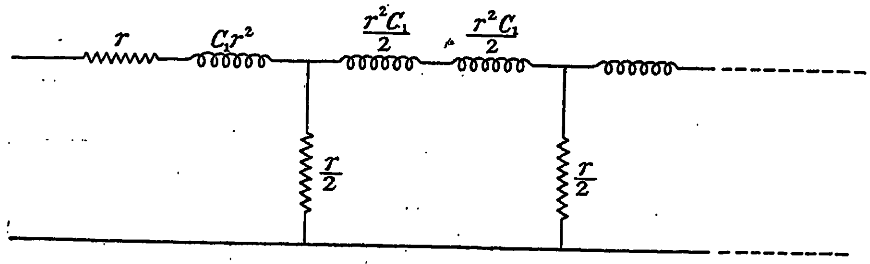

FIG. 14.

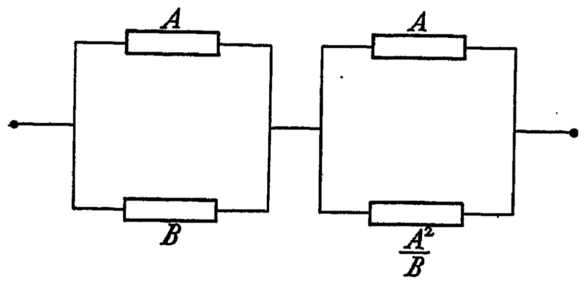

FIG. 15.

If we connect a circuit as Fig. 12 in parallel with the circuit of Fig. 10, we shall reduce the impedance of the combination to r. The impedance r^2/Z' is the reciprocal with respect to r of an infinite series of Π section (Fig. 11), and is therefore an infinite series of **T** sections of Fig. 13, having for series members inductances equal to $\frac{1}{2}r^2C_1$, and for shunt members resistances equal to $\frac{1}{2}r$. Hence by shunting the infinite line by the network of Fig. 14 the impedance is reduced to r, i.e. $\sqrt{(L/C)}$. In practice the use of quite a small number of sections of this artificial line suffices to reduce the impedance of the combination to a close approximation to a non-inductive resistance.

Results of similar form follow for the other **T** sections.

From the Π section, except for the case when $S = 0$, other shunting networks can be deduced in the same way, or, by using the result that the network of Fig. 15 is identically equal to A, networks which when placed in series with a uniform line reduce its impedance to a resistance can be obtained.

For the Π-section case where $S = 0$, by a double application of the result of Fig. 8 two networks can be obtained which together shunted across the line reduce its impedance to a resistance.

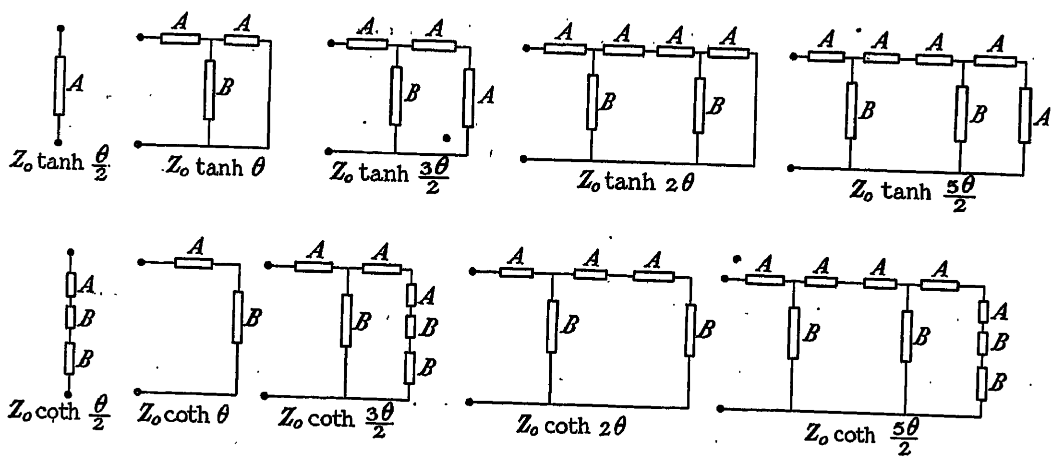

FIG. 16.

CURRENT-TRANSFORMER METHODS OF PRODUCING SMALL, KNOWN VOLTAGES AND CURRENTS AT RADIO FREQUENCIES FOR CALIBRATING PURPOSES.

By D. W. Dye, B.Sc.

[From the National Physical Laboratory.]

(*Paper first received* 31*st October*, 1924, *and in final form* 27*th April*, 1925; *read before the* Wireless Section 4*th March*, 1925.)

Summary.

A method is outlined whereby known, small radio-frequency voltages may be produced. The method consists of an arrangement of a current transformer, across the secondary of which is a suitable resistance of known value. A thermo-junction or other device serves to measure or to set the primary current. Voltages from a few microvolts to a few tenths of a volt may be conveniently produced. The nature and extent of the errors of the method are discussed, and the precautions necessary to reduce these to a negligible amount are indicated. Various uses of the method are touched upon and the limitations of the method are given.

An appendix gives a simple analytical treatment of the iron losses in the core of a current transformer at radio frequencies, in so far as these affect the ratio of the transformer. The phase displacement of the currents is, however, not discussed.

(1) Introduction.

In connection with investigations on the strength and direction of received radio signals, the strength and direction of atmospheric disturbances, measurements of the amplification of radio-frequency amplifiers and in certain classes of decrement measurement, it becomes necessary to calibrate some part of the apparatus by the help of a known, very small voltage or current applied to a particular portion of the system concerned.

A number of methods for the production of known voltages are in use by various investigators. These methods fall into two main classes:—

(1) Potential difference between the ends of a resistance. The resistance usually forms a portion of a potential divider when the voltage required is very small indeed.
(2) Electromotive force induced in the secondary coil of a mutual inductance.

These two methods are discussed at length in a paper by H. G. Möller and E. Schrader,* and a number of typical cases have been taken with a view to indicating the nature and extent of the inaccuracies which may be introduced unless certain precautions are taken.

Certain disadvantages of these two methods have not, however, been explained. With regard to class (1), when the desired voltage is very small (below 500 μV) it is necessary to use a very low resistance if the measured current through it is used as a basis of calculation. In such a case the residual inductance of the resistance may introduce large corrections. If the voltage is deduced from the ratio of a low and a high resistance in series, recourse must be had to an instrument capable of directly reading at least 1 or 2 volts, unless a very high resistance is used in series so that the total voltage may be read on an electrostatic instrument. The self-capacity of such a resistance and the mutual capacity to other parts of the apparatus will again introduce serious corrections. This method has, however, been successfully used in America * for low radio frequencies. The chief advantage of resistance methods is that, except for the corrections, the voltage produced does not depend upon frequency.

With regard to class (2), the main source of trouble is the relatively high impedance of the secondary winding of the mutual inductance. If the secondary is considered to be the source of the required electromotive force, then this source possesses a high internal impedance and hence the terminal voltage will depend upon the impedance of the circuit to which it is applied, unless this is very high. The capacity between primary and secondary windings, in such a case, may also introduce considerable changes in the effective secondary voltage. Finally, the voltage produced depends to the first order upon frequency.

The method is, however, extremely flexible, and when used with precautions, is capable of giving accurate results. Its special sphere of usefulness is at low radio frequencies.

The method described in the present paper partakes of the good qualities of both the foregoing methods and is believed to be to a large extent free from the disadvantages of either.

(2) Principle of the Method.

The essential feature of the method is the use of a current transformer whereby a known, very small current may be produced from a larger, directly measured one. The principles underlying current transformers for radio frequencies have been set out in a previous paper by A. Campbell and the present author.† This paper deals with the use of such transformers for the measurement of large currents. Reference is also made to the use of such apparatus for the measurement of very small currents; but there are serious limitations

* "On the Production of Small Alternating Voltages of Known Value," *Jahrbuch der Drahtlosen Telegraphie*, 1923, vol. 22, p. 66.

* R. Bown, G. C. Englund and H. Friis: "Radio Transmission Measurements," *Proceedings of the Institute of Radio Engineers*, 1923, vol. 11, p. 115.

† "On the Measurement of Alternating Electric Currents of High Frequency," *Proceedings of the Royal Society*, A, 1914, vol. 90, p. 621.

to the use of transformers in this direction. There are, however, no drawbacks to the use of current transformers for producing known, small currents in a secondary circuit, so long as certain conditions in the circuit are satisfied. In order to produce a known, small voltage we have only to pass the small secondary current through a moderate resistance provided with potential leads. The system is therefore as shown in Fig. 1.

Current of the value of a few mA to 100 mA is provided by a local high-frequency source. This current is measured by a heater and thermo-junction, and also passes through the primary winding (N_1) of the transformer. This winding consists of one or a few turns (N_1) of stranded wire and has an inductance which is, in general, negligibly small compared with the main inductance in the source.

The secondary winding consists of N_2 turns uniformly wound around a bundle of iron ring stampings, and thus forms a toroidal iron-cored inductance. This winding is connected to a non-inductive resistance R having a value between 1 and 50 ohms. This resistance should have separate potential leads in order that contact resistances may introduce no uncertainties, and also to eliminate or compensate residual inductance if necessary. The desired potential difference is obtained from the potential leads and is applied to the apparatus under test.

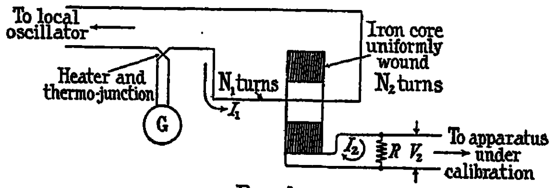

FIG. 1.

Within certain limits discussed below, the current I_2 traversing R is independent of the value of R and so a considerable range of voltage is available. The voltage V_2 is, to a close approximation, given by

$$V_2 = \frac{N_1}{N_2} I_1 R \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The current transformer is, of course, only a special form of mutual inductance, and need not take the form given above.

In more general terms of mutual and secondary self-inductances Equation (1) becomes :—

$$V_2 = \frac{M}{L_2} I_1 R \quad . \quad . \quad . \quad . \quad . \quad (2)$$

If, however, a mutual inductance of the more usual form is used it becomes necessary to measure or calculate M and L_2 in order to determine their ratio. With suitably designed windings there will be no great uncertainty of ratio if M and L_2 are measured at low frequencies.

There are, however, a number of advantages attached to the interlinking of the primary and secondary windings. We then make use of the principle that the line-integral $\int H dl$ around a conductor or bundle of conductors is constant and independent of the path followed. If, therefore, the secondary winding is of uniform cross-section and uniformly wound in such a manner as to have no appreciable leakage magnetic field when linked with the primary, the mutual inductance will be independent of the location of the two windings with respect to one another, and the ratio of secondary self-inductance to mutual inductance will be exactly equal to the ratio of secondary to primary turns and will be independent of all the dimensions.

It is only necessary in such a case to take a ring-shaped core of uniform section and uniform permeability and wind it with a uniform winding to form the secondary circuit. In some cases the core may be magnetic, but in others it is preferably non-magnetic. The primary may then consist of between 1 and 20 turns or even more. These may theoretically be wound in any manner whatever so long as they link the secondary. They are, however, better if symmetrically disposed about the secondary. When the secondary winding is effectively short-circuited the ratio of secondary to primary current will be N_1/N_2 to a high degree of accuracy, and no measurement of self-inductance or mutual inductance is necessary. This ratio will also be almost independent of frequency.

Two examples are given below to indicate the range of voltages conveniently available.

Very small voltage.

$I_1 = 2 \times 10^{-3}$ ampere
$N_1 = 1$ turn
$N_2 = 200$ turns
$R = 0{\cdot}1$ ohm (not recommended at high frequencies)
$E_2 = 1 \times 10^{-6}$ volt

Moderate voltage.

$I_1 = 100 \times 10^{-3}$ ampere
$N_1 = 10$ turns
$N_2 = 100$ turns
$R = 50$ ohms
$E_2 = 0{\cdot}5$ volt.

(3) CONDITIONS GOVERNING THE ACCURACY OF THE METHOD.

There are two sets of conditions governing the accuracy of the method :—

(*a*) Those inherent in the method itself.
(*b*) Those depending upon the nature of the circuit to which it is applied.

Dealing with (*a*) first, the equations connecting primary and secondary currents in an air-core current transformer are as follows :—

(i) *For damped or modulated wave-form.*—

$$\frac{I_2}{I_1} \doteq \frac{M}{L_2}\left[1 - \frac{R_2\{R_2 - (\delta_1/\pi)L_2\omega\}}{2L_2^2\omega^2}\right] \quad . \quad . \quad (3)$$

(ii) *For sine-wave form.*—

$$\frac{I_2}{I_1} \doteq \frac{M}{L_2}\left(1 - \frac{R_2^2}{2L_2^2\omega^2}\right) \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where δ_1 = logarithmic decrement per whole period,
L_2 = total self-inductance of the secondary circuit,
M = mutual inductance between primary and secondary,
R_2 = total effective resistance of secondary circuit.

Considering only the sine-wave case, it is seen that the only term involving frequency is the correction term $\frac{1}{2}\{R_2/(L_2\omega)\}^2$. If it is desired to keep this correction term not greater than 0·5 per cent, the value of $R_2/(L_2\omega)$ must be not greater than 0·1. For various reasons an upper limit of R_2 should be about 50 ohms. In an extreme case in which ω is only 10^5 it will be necessary to make L_2 as great as 5 mH. To achieve such a value even with an iron core would require a considerable number of turns on the secondary winding. If, at the same time, we wished to produce a considerable voltage it would be necessary to provide a considerable number of primary turns—about 20. At such a low frequency, however, there will be no objection to this, since a very large inductance in the generator oscillatory circuit will be inevitable.

For the case of damped waves, an inspection of Equation (3) shows that for all ordinary values of δ_1 the term $(\delta_1/\pi)L_2\omega$ will be not greater than R_2 unless R_2 is very small, in which case the whole correction will still be small. We may write $L_2\omega = qR_2$; Equation (3) then becomes

$$\frac{I_2}{I_1} \doteq \frac{M}{L_2}\left\{1 - \frac{1}{2q}\left(\frac{1}{q} - \frac{\delta_1}{2\pi}\right)\right\} \quad . \quad . \quad (5)$$

As an example, if $q = 10$ then $\delta_1/(2\pi)$ would need to be equal to 0·2 before the correction term became + 0·5 per cent on account of δ_1. In such a case δ_1 would need to be 1·26.

Sine-wave modulated waves may be considered to be of the form

$$i = I_0(1 + r \sin ft) \cos \omega t$$

This may be considered to be equivalent to three independent sine-wave sources having the values

$$I_0 \cos \omega t + \tfrac{1}{2}I_0 r \sin (\omega + f)t + \tfrac{1}{2}I_0 r \sin (\omega - f)t$$

The R.M.S. current will then take the form

$$I_{R.M.S.} = \frac{1}{\sqrt{2}}I_0\sqrt{(1 + r^2)}$$

In practice the three frequencies are not very different from one another, so that the mean correction term in (4) will be almost identical with that for a single sine-wave case. The worst case would be that of a completely modulated wave with the carrier wave suppressed. In such a case the correction term would be increased in the ratio of $1 : (1 + f^2/\omega^2)$. The value of f is never likely to be greater than 1/20th of ω. In this case the increase in the correction term is entirely negligible.

In the case of an iron-cored transformer the hysteresis and eddy-current losses in the iron introduce a correction term which is proportional to R_2 and not to R_2^2. This question is dealt with more fully in the Appendix.

The additional term which will be inside the bracket of Equation (4) takes the form

$$- R_2\frac{m_2^2 S}{L_2^2(N^2\omega^2 + S^2)}$$

where the iron losses are represented by a tertiary circuit having constants of resistance and inductance equal to S and N respectively and coupled with the secondary circuit by mutual inductance m_2. The correction term due to the iron losses may be very conveniently written

$$\frac{\pi}{4}\delta i\frac{R_2}{L_2\omega}$$

where δi represents the logarithmic decrement * of the magnetic core. This term tends to become more important than the second term of Equation (4) if the flux density in the iron is not kept very low. Since δi may approach unity in an extreme case it is very desirable to keep $R_2/(L_2\omega)$ as small as convenient. In general a value of 0·05 should be considered as a working limit for the method when using an iron-cored transformer.

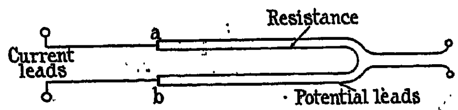

FIG. 2.

When the method is in use it is easy to see if the correction terms are small. There are two ways of doing this :—

(a) To vary the ratio of transformation and then alter R to bring the nominal voltage to the same value. There should be no alteration in the voltage as indicated on the amplifier or other device under calibration.

(b) A resistance of 10 ohms or so may be added in the secondary circuit in series with the standard resistance across which the desired voltage is produced. There should be no change in I_2 and hence no change in the voltage across R. Both these methods have been tried and no appreciable change in voltage across R could be detected in a case in which this calibrating method was used in connection with measurements on signal strength. In general, the surest way of ascertaining that the value of R chosen is not too large is to add a resistance equal to $\frac{1}{2}R$; the total correction will then become about twice what it was before. Hence the change noted can be used to correct the original observation if found great enough.

There are two other quantities associated with the method which may introduce errors in the value of the electromotive force at the potential points of R. These are, residual inductance l in the resistance, and capacity between the points "a, b" of Fig. 2. Such

* The logarithmic decrement of the magnetic core may be defined as the ratio $\Delta R/(2\pi\Delta L)$, where ΔR and ΔL are the increases in effective resistance and effective inductance respectively of an inductive coil, due to the presence of the magnetic core. The ratio is independent of the shape or size of the core.

capacity will include the self-capacity of the secondary winding and of the leads connecting R to it.

For the capacity effect we may consider R to be replaced by a condenser and a resistance in parallel. The equivalent series impedance of such a combination is given by

$$R_0 = \frac{R}{1 + R^2C^2\omega^2} \doteqdot R(1 - R^2C^2\omega^2)$$

and
$$L_0\omega = - R^2C\omega$$

We may consider the total ingoing current I_2 as being entirely unaltered by the addition of C. We have, therefore,

$$\begin{aligned} E_2 &= I_2\sqrt{\{R^2(1 - R^2C^2\omega^2)^2 + (R^2C)^2\omega^2\}} \\ &\doteqdot I_2\sqrt{\{R^2(1 - R^2C^2\omega^2)\}} \\ &\doteqdot I_2R(1 - \tfrac{1}{2}R^2C^2\omega^2) \end{aligned}$$

If we take an extreme case, we may have $R = 50$ ohms, $C = 200\,\mu\mu$F, $\omega = 10^7$. The correction then becomes equal to 0·5 per cent.

The second source of error resides in the inductance of the resistance. Instead of $E_2 = RI_2$ we shall have

$$E_2 = RI_2\sqrt{\left(1 + \frac{l^2\omega^2}{R^2}\right)}$$

where l is the residual inductance of the resistance.

If the correction term is small, this may be written

$$E_2 = RI_2\left(1 + \frac{l^2\omega^2}{2R^2}\right)$$

Taking an extreme case, and assuming that the correction term must not exceed 0·5 per cent, we have $l\omega = R/10$.

If $R = 0\cdot1$ ohm and $\omega = 10^7$,

$$l = 1 \times 10^{-9} \text{ henry, i.e. 1 cm only.}$$

If the resistance is a four-terminal one, the effective inductance will include mutual inductance between the current and potential leads. Use can be made of this property to compensate the true residual inductance so as to cause the effective residual inductance to be strictly zero, as first shown by Campbell.*

There are, however, considerable uncertainties attaching to the measurement of residual inductance of low resistances to such an accuracy as 0·001 μH. It is considered undesirable, therefore, to use resistances smaller than 1 ohm at high radio frequencies. Even with this value, care should be taken in the construction and mounting of the resistance and its leads. These should be arranged in a manner which will bring about a compensation in the potential leads if accuracy is required at high radio frequencies. If the resistance consists of a loop of wire only 1 cm or so long doubled closely on itself, its inductance will be only of the order 0·01 μH, a value of importance only at frequencies above 10^6 per second. A suitable form of resistance is shown in Fig. 2.

It will be convenient to discuss the effects of the circuit to which the transformer is connected, when describing some of the applications and the convenient arrangement of the circuits.

(4) Arrangement of the Apparatus.

A suggested outlay of a valve generator apparatus suitable for the method is given in Fig. 3. The oscillatory circuit consists of toroidal inductance L_1 and screened adjustable capacity C_1; this circuit is outlined with heavy lines and shows a two-turn primary winding on the current transformer. A thermo-junction and a galvanometer G serve to measure the primary current. The parts of the circuit at a high alternating potential above that of the point marked B are enclosed in a metal-lined box which is connected to the circuit at B. A large condenser C_2 across the anode battery serves to keep its impedance practically zero. The only external lead requiring a screen is that going to the insulated, fixed set of plates of the variable condenser. If this scheme is carried out there is practically no potential difference between any two points in the external circuit or the oscillator, except at the place where it is required.

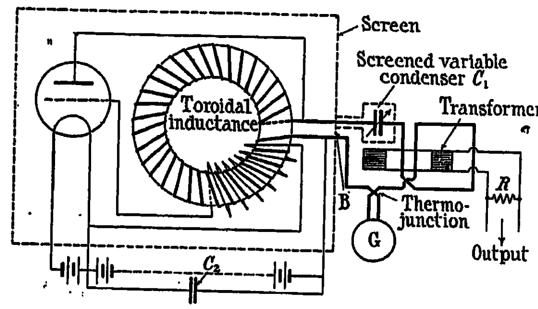

Fig. 3.

It is not essential to use a toroidal form of inductance in every case, but where highly sensitive apparatus is being calibrated the superiority of this form from the point of view of screening will be evident. In such a case it is really only necessary to provide electrostatic screening against capacity coupling between the oscillator and the apparatus being calibrated. Some measurements made on toroidal coils showed that their effective self-capacity was only about 50 per cent greater than those of the single-layer cylindrical type of the same overall diameter.

When toroidal coils are used in a one-valve oscillator it is essential to use a separately wound grid inducing coil. This coil should not be completely overwound on the main oscillator coil but may extend from $\frac{1}{4}$ to $\frac{1}{3}$ the distance round the ring, commencing at the point connected to B.

In oscillator circuits used in this manner for calibrating purposes it is desirable to keep the capacity C_1 as large as possible. A capacity of 0·002 μF is not too large in most cases.

Typical transformer.—A transformer constructed at the National Physical Laboratory for general laboratory use consists of a secondary winding of 100 turns uniformly wound around the core. There are three primary windings of 1, 5 and 10 turns respectively. The turns of

* "Compensation of Residual Inductance in Four-terminal Resistances," *Electrician*, 1908, vol. 61, p. 1000.

the secondary winding are located in position by small notches spaced around the four circular edges of a ring-shaped ebonite box in two halves. This box contains the iron stampings forming the core. These latter are of thin stalloy and have a cross-sectional area of about 2 cm^2. In some cases where relatively large voltages are required at low radio frequencies it is desirable to use a larger cross-section of iron than 2 cm^2. A larger resistance may then be used without increasing the flux in the iron to a value at which the iron correction term becomes serious.

(5) Applications of the Method.

The method of applying the voltage to other apparatus will, of course, vary considerably according to the conditions which must be maintained in the apparatus, and to its impedance. The factors to be considered are :—

(1) The effect, on the applied voltage, of the circuit to which it is applied.

(2) The effect, on the circuit, of the application or introduction to it of the resistance across which the applied voltage is produced.

(i) *Calibration of an amplifier.*—When the amplifier is of a type possessing the very high input impedance of the grid-filament circuit of the first valve, the attachments of this to the terminals of the resistance will not alter the calibrating voltage. The main precautions to be taken then consist in so arranging the disposition and connections of the parts that no electromotive forces, other than that directly applied, may operate on the amplifier system. In a case where the grid filament is directly connected to the resistance, any capacity coupling to this valve will be of negligible consequence, but when the grid and filament are separated by a small condenser of comparatively high impedance the leads and other parts of the grid circuit may receive an alternating potential which is not negligibly small, as the result of capacity coupling to portions of the generator system. On this account it is desirable to connect the transformer primary at the high-tension battery end of the toroidal inductance and not at the inductance end joined to the anode of the generator valve. In the latter case the capacity coupling between the primary and secondary of the transformer, together with the capacity of the amplifier valve to earth, constitute a circuit in which a parasitic current will flow. As a result an additional E.M.F. will be applied to the grid-filament circuit of the valve of the amplifier.

Some measurements made on transformers gave values for the mutual capacity varying between the limits of 1·5 $\mu\mu$F and about 10 $\mu\mu$F, depending upon the number of primary turns.

The most rigorous test to apply, to ensure that these parasitic E.M.F.'s are not of importance, is to reduce the applied voltage to zero by making R zero. There should now be no difference in the amplifier measuring circuit when the calibrating oscillator is switched off and on. In general when a very sensitive amplifier is under calibration it is impossible to realize this condition perfectly, unless complete electromagnetic screening is adopted as well as inserting the primary of the transformer on the anode battery side of the oscillator inductance.

(ii) *Calibration of a receiving system.*—When it is desired to introduce a known E.M.F. into an oscillatory circuit of low resistance, two effects will occur. The applied voltage will be reduced, owing to the shunting effect of the circuit on the resistance. Also, the voltage amplification of the receiving circuit will be reduced, owing to the increase of its effective resistance consequent upon the addition of the resistance R.

If the oscillatory circuit has an effective resistance S, then when in resonance it will reduce the voltage across the terminals of R in the ratio $S/(R+S)$. Also, by reason of the increase in effective resistance of the oscillatory circuit from S to $(S+R)$, the voltage amplification of the circuit will be reduced in the ratio $S/(R+S)$. The nominal voltage applied must therefore be multiplied by the factor $S^2/(S+R)^2$ in order to render it equivalent to an unaffected voltage operating on the unaffected resistance of the receiving circuit. Since, in general, the effective resistance of a receiving system will not be greater than 20 or 30 ohms and may be as low as 1 or 2 ohms, the correction terms may become very serious, and would entail an accurate knowledge of S. It is suggested, therefore, that this method of applying a voltage to a receiving system must be used with great caution and with full knowledge of the conditions of the receiving system.

(iii) *The provision of a very small current or voltage in an inductive coil—such as a Bellini-Tosi inducing coil.*—In such a case the conditions are quite different, since the transformer is not effectively short-circuited. In this use of the method it will be essential to use an air-core transformer in order that the secondary inductance may be invariable with frequency and current.

The formulæ for current ratio will be as in Equations (3) and (4), but instead of L_2 we shall have (L_2+L_3), where L_3 is the self-inductance of the coil through which the desired current is passing. The secondary winding of the transformer should again be toroidal in form and may be wound conveniently on a frame made up of two ebonite rings separated by three ebonite pillars. If the ratio of secondary to primary turns is N_2/N_1, then the secondary current in the external coil will be given by

$$\frac{I_3}{I_1}=\frac{N_1}{N_2}\cdot\frac{L_2}{L_2+L_3}\left\{1-\frac{R_t^2}{2(L_2+L_3)^2\omega^2}\right\} \quad . \quad (6)$$

in which R_t is the total effective resistance of the secondary circuit.

When L_3 is not small compared with L_2 it may become necessary to take account of the self-capacities of the secondary winding and of the external winding; the capacity of the connecting leads will also need to be included. For the purpose of making this correction we may consider these capacities to be represented by a single concentrated capacity shunted across the secondary winding. Calling this capacity C it will be found that the ratio of current in the external coil to that in the primary is given by

$$\frac{I_3}{I_1}=\frac{N_1}{N_2}\cdot\frac{L_2}{L_2+L_3}\left\{1-\frac{R_t^2}{2(L_2+L_3)^2\omega^2}+\frac{L_2L_3C\omega^2}{L_2+L_3}\right\} \quad (7)$$

It will be seen that the corrections are of opposite signs. Since, however, the first term varies inversely as ω^2, whilst the second one varies directly as that quantity, a compensation cannot be obtained over any useful range of frequency.

It is desirable, in general, to keep L_2 fairly large compared with L_3. In this case L_2 and L_3 do not need to be known with very high accuracy. If, however, $L_3C\omega^2$ is as great as $0{\cdot}1$ it would be better to keep L_2 about the same value as L_3 in order to reduce the value of the second correction term.

Except at very low radio frequencies the first correction term will not be large, since we are not adding resistance intentionally in the secondary circuit.

For recommendation and permission to publish the method, the author's thanks are due to the Committee of the Radio Research Board on Standards and the Propagation of Waves established under the Department of Scientific and Industrial Research, under whose auspices the work was done. He is also indebted to Mr. Hollingworth, of the Wireless Division of the National Physical Laboratory, where the method has been adopted, for confirmatory information regarding some of the points referred to in the paper.

APPENDIX.

IRON-CORED CURRENT TRANSFORMER.

Consider iron losses as equivalent to a closed tertiary circuit N_1S carrying an instantaneous current i_3' (see Fig. 4).

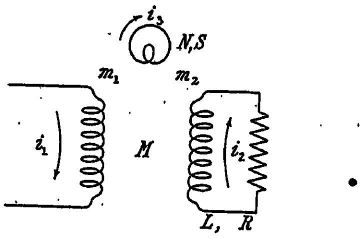

FIG. 4.

We have

$$i_2(R + La) + e_2 = 0 \quad . \quad . \quad . \quad . \quad (8)$$

$$i_3(S + Na) + e_3 = 0 \quad . \quad . \quad . \quad . \quad (8a)$$

$$e_2 = i_1Ma + i_3m_2a \quad . \quad . \quad . \quad . \quad (9)$$

$$e_3 = i_1m_1a + i_2m_2a \quad . \quad . \quad . \quad . \quad (9a)$$

where

$$a = j\omega$$

from which

$$i_3 = -\frac{i_1m_1a + i_2m_2a}{S + Na}$$

and

$$i_2(R + La) + i_1Ma - \frac{m_2a}{S + Na}(i_1m_1a + i_2m_2a) = 0$$

$$i_2\left\{(R + La) + \frac{m_2^2\omega^2}{S + Na}\right\} = -i_1\left\{Ma + \frac{m_1m_2\omega^2}{S + Na}\right\}$$

whence

$$\frac{I_2^2}{I_1^2} = \frac{(MN - m_1m_2)^2\omega^4 + M^2S^2\omega^2}{\{(LN - m_2^2)\omega^2 - RS\}^2 + (LS + RN)^2\omega^2} \quad . \quad (10)$$

$$= \frac{M^2\omega^2\left(N\omega - \dfrac{m_1m_2\omega}{M}\right)^2 + M^2\omega^2S^2}{L^2\omega^2\left(N\omega - \dfrac{m_2^2\omega}{L} - \dfrac{RS}{L\omega}\right)^2 + L^2\omega^2\left(S + \dfrac{RN}{L}\right)^2} \quad (11)$$

If we assume m_1m_2 to be small compared with MN, we shall find that

$$\frac{I_2^2}{I_1^2} = \frac{M^2}{L^2}\left[1 - \frac{R^2}{L^2\omega^2} + \frac{2m_2^2\omega^2}{N^2\omega^2 + S^2}\left(\frac{N}{L} - \frac{Nm_1}{Mm_2} - \frac{RS}{L^2\omega^2}\right)\right] \quad (12)$$

The only important term due to the tertiary circuit is the term $RS/(L^2\omega^2)$, since $(Nm_1)/(Mm_2) \doteq N/L$. We therefore have :—

$$\frac{I_2^2}{I_1^2} \doteq \frac{M^2}{L^2}\left[1 - \frac{R^2}{L^2\omega^2} - \frac{2m_2^2RS}{L^2(N^2\omega^2 + S^2)}\right] \quad . \quad (13)$$

The relative importance of the second correction term will depend upon the nature and extent of the iron losses. There is a lack of information regarding the losses in iron sheets at very small alternating inductions of radio frequency. In a typical case of a well designed transformer the effective R.M.S. magnetizing force will be of the order of 1×10^{-4} to 5×10^{-4}. At such weak magnetizations the hysteresis losses become small compared with the eddy-current losses, since the former vary as a power of B which is considerably greater than 2. The second correction term in Equation (13) cannot be used in its present form owing to the uncertainties attaching to the values of m_2, S and N, and to the fact that these quantities will vary with $B_{max.}$ and frequency. It is therefore desirable to introduce some more fundamental term to express the effects of the losses in the iron core. For this purpose it is very convenient to think of the core as possessing a logarithmic decrement δi given as the ratio $\Delta R/(2n\Delta L)$, where ΔR and ΔL are the increments of resistance and inductance respectively conferred upon any circuit in virtue of the iron core.

Consider the single winding of N_2 turns of the transformer on a circular core of magnetic material of effective permeability μ and of cross-section and length s and l respectively.

We shall have

$$L = \frac{1{\cdot}257 \times N_2^2 \times \mu \times s \times 10^{-8}}{l} \text{ henry}$$

Let a current I_e be flowing in the winding, of such value as to produce the value of H actually existing in the current-transformer core in normal use. We shall have

$$H = \frac{4\pi N_2I_e}{10l} \quad . \quad . \quad . \quad . \quad . \quad (14)$$

The circuit will have a resistance component r representing the iron losses. This resistance will be such that $rI_e^2 = W =$ iron losses. We have also $r/(2Ln) = \delta i$.

Reverting for a moment to the transformer case, we have, at the secondary terminals, a voltage E_2 given by

$$E_2 = RI_2$$

The value of H necessary to produce this value of E_2 will be given by

$$E_2 = 2\pi N_2 H\mu sn \times 10^{-8} \quad . \quad . \quad . \quad (15)$$

where n = frequency.

We can equate the two values of H in (14) and (15) thus:—

$$\frac{4\pi N_2 I_s}{10l} = \frac{E_2 \times 10^8}{2\pi N_2 \mu sn}$$

whence

$$I_s = \frac{RI_2 \times 10^9 \times l}{8\pi^2 \times N_2^2 \mu sn}$$

Now the iron losses are given by rI_s^2. We have

$$r = \delta i \times 2Ln$$

$$= \delta i \times \frac{2n \times 1 \cdot 257 N_2^2 \mu s \times 10^{-8}}{l}$$

The losses become

$$Wi = \frac{\delta i R^2 I_2^2 l \times 10^9}{8\pi^3 \times N_2^2 \mu sn} = \frac{\delta i R^2 I_2^2}{2\pi^2 nL}$$

The secondary losses are equal to RI_2^2.

The ratio of the losses, σ, is given by

$$\sigma = \frac{Wi}{RI_2^2} = \frac{\delta i}{\pi} \times \frac{R}{L\omega} \quad . \quad . \quad . \quad (16)$$

$$= \frac{I_3^2 S}{I_2^2 R} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

in the equivalent of Fig. 4.

From Equations (6) to (9) we shall find that

$$\frac{I_3^2}{I_2^2} = \frac{m_1^2 R^2 + (m_1 L - m_2 M)^2 \omega^2}{M^2 S^2 + (MN - m_1 m_2)^2 \omega^2} \quad . \quad . \quad (18)$$

Since the primary and secondary windings are similarly situated with respect to the fictitious tertiary winding representing the iron losses, we may assume that $m_1/M = m_2/L$. We shall also have $m_1 m_2$ small compared with MN, so that

$$\frac{I_3^2}{I_2^2} = \frac{m_1^2 R^2}{M^2(S^2 + N^2\omega^2)} = \frac{m_2^2 R^2}{L^2(S^2 + N^2\omega^2)} \quad . \quad (19)$$

If we substitute σ from (16) into (18) we get

$$\sigma = m_2^2 RS/[L^2(S^2 + N^2\omega^2)]$$

so that 2σ is equal to the second correction term of Equation (13). But σ by (16) is equal to $\delta iR/(\pi L\omega)$.

We see, therefore, that, in terms of the fundamental properties of the iron, Equation (13) may be written

$$\frac{I_2}{I_1} \doteq \frac{M}{L}\left[1 - \frac{R^2}{2L^2\omega^2} - \frac{\delta i}{\pi} \cdot \frac{R}{L\omega}\right] \quad . \quad . \quad (20)$$

The quantity δi may vary over very wide limits according to the quality and thickness of the iron and according also to the frequency and the value of $H_{max.}$ to which it is exposed. With thin stalloy (0·02 mm thickness) and at a frequency of 10^5 cycles per second, δi has values varying between 0·01 and 0·1 for a range of $H_{max.}$ from a very small value up to $H = 0 \cdot 002$. On the other hand, with thicker iron and at higher frequencies δi may be as high as 1·5.

DISCUSSION BEFORE THE WIRELESS SECTION, 4 MARCH, 1925.

Mr. F. E. J. Ockenden: The author does not refer to the probable accuracy of his method, i.e. the accuracy which one could hope to attain by the use of cores of convenient dimensions and windings and the usual values of M. I have recently been experimenting with a current transformer of turn ratio 1/1 with 30 primary ampere-turns, using a differential thermo-couple to detect any difference between the primary and secondary currents. A typical result is as follows: Primary current, 1 ampere; primary turns, 30; secondary turns, 30; frequency, 1×10^6; secondary watts, 0·5; difference between primary and secondary currents, 1·5 per cent. In the second example given by the author the number of primary ampere-turns is 1·0 and the secondary watts = 0·005. Assuming that the error per cent falls as the square of the flux and therefore as the square of the secondary load, but varies inversely as the primary ampere-turns, the error would be $1 \cdot 5 \times (30/10) \times (0 \cdot 005/0 \cdot 5)^2 = 0 \cdot 0045$ per cent, or about 5 parts in 100 000. This appears to be exceedingly good. I do not know if it is the sort of accuracy which the author himself would expect. It occurs to me, however, to wonder whether, when the secondary load is exceedingly small, the core loss of the transformer is really the deciding factor. It is very difficult to wind an iron-core transformer with two windings so perfectly linked that the leakage flux is really nil, and at frequencies of between 10^5 and 10^6 a very small leakage

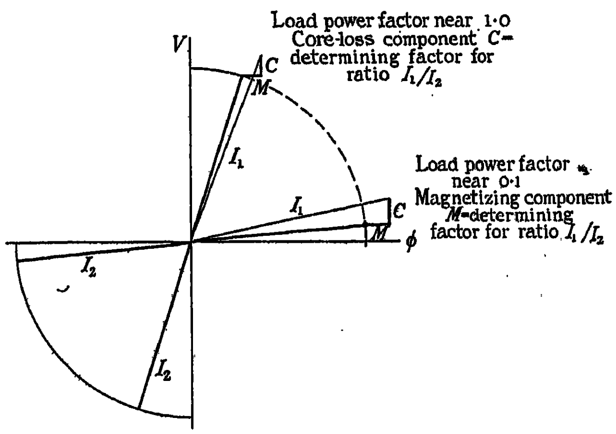

FIG. A.

flux will add to the secondary load a large inductance, which will reduce its apparent power factor to a figure far below unity. In the example mentioned before,

the power factor appeared to be only 0·40, i.e. cos ϕ = about 65°, and as the non-inductive component is reduced to lower and lower values the angle will approach nearer and nearer to 90°. The primary current will, of course, follow this very closely and the internal power factor of the transformer will remain very high, but, as the power factor of the load decreases, it will move more nearly into phase with the magnetizing component of the primary current and nearly in quadrature with the core-loss component. The latter will then have practically no effect on the transformer ratio, whereas the former or magnetizing component must be added vectorially to the primary current, or in the case of a 1/1 ratio may be deducted from the secondary current (see Fig. A). In reference to Fig. 3, the author mentions the necessity of carefully screening the oscillator circuit from the apparatus being calibrated, and states that this is very difficult to do perfectly. If it is difficult in the case of a small valve oscillator, it may be imagined that it is almost impossible however, when such a method is used for the purpose of signal-strength measurements, for here the secondary forms part of the antenna system and it is always the E.M.F. induced into the antenna system which is required to be simulated. We are thus not concerned with other than induced E.M.F.'s. In connection with signal-strength measurements, it is often necessary to go below the limiting value of 1 μV quoted by the author; for instance, in practical measurements I often go as low as 0·2 μV, and I should like to ask the author what arrangement of N_2 and R he would recommend for this purpose. The method I use is shown in Fig. C. Here M is a calibrated variable mutual inductance having a maximum value of the order of 1 μH, the primary being fed from a screened oscillator. The secondary, which has an inductance, L, of about 20 μH, is shunted by a non-inductive resistance, R, of 100 ohms, of which 1 ohm is tapped off and included in a frame-antenna circuit. The voltage, E, across the 1 ohm is given as a function of I_1, the current in the primary of

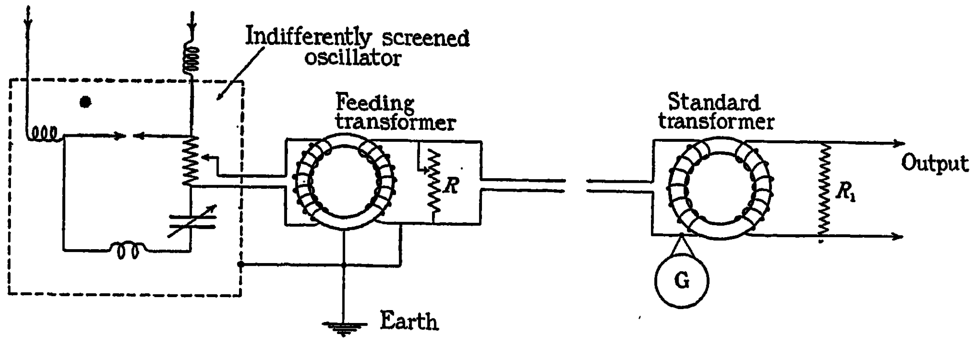

FIG. B.

in the case of a 2 kW Poulsen arc such as I have been using. I have tried screening the test apparatus only, but, apart from burying it, this seems almost as difficult. I have, however, successfully solved the problem by the use of a second iron-cored transformer. Thus, referring to Fig. 3, imagine the transformer shown to be merely a feeder transformer of indifferent accuracy. The core and secondary winding of this transformer may be earthed and the leads marked "output" may be carried away for a considerable distance and then be used to feed the primary of a second transformer, used as a standard, the thermo-couple being inserted in the primary of this second transformer. By using the resistance marked R as a variable shunt across the feeding transformer secondary, the current in the standard, and therefore the potential across R_1, may be adjusted to a nicety. At the same time the whole of the standard gear and the amplifier under test may be placed remote from the generator and exceedingly free from the parasitic potentials which the author mentions as being difficult to eliminate (see Fig. B).

Mr. F. E. Nancarrow: In the introduction to the paper the author states, in referring to the second method of producing small E.M.F.'s, that a disadvantage of the method arises from the high impedance of the secondary winding. No such disadvantage exists, the mutual inductance, and M, the value of the mutual inductance, by the following:—

$$E = \frac{RI_2}{100} = \frac{R}{100}\cdot\omega MI_1(R^2+\omega^2L^2)^{-\frac{1}{2}}$$
$$= \frac{R}{100}\cdot\frac{\omega MI_1}{R}\left\{1-\frac{1}{2}\left(\frac{\omega L}{R}\right)^2+\dots\right\}$$
$$\doteq \omega MI_1\left\{1-\frac{1}{2}\left(\frac{\omega L}{R}\right)^2+\dots\right\}$$

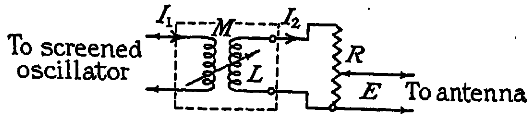

FIG. C.

Hence, provided that R is sufficiently large compared with ωL, the voltage across the tap is always proportional to I_1 and M. In a practical case where n = 60 000 p.p.s., i.e. $\omega = \frac{1}{3}\times 10^6$ (approx.) we have $\omega L = 20/3$ ohms and $\omega L/R = 1/15$, or $(\omega L/R)^2 = 1/225$, i.e. this term would involve a correction of less than $\frac{1}{2}$ per cent, which is negligible in practical measurements of signal strength. For the measurement of I_1 I actually use a valve voltmeter, which gives the voltage

across a condenser in the circuit including the primary of the mutual inductance, and from which I_1 is derived in the usual way. The author's method is of course fundamental, inasmuch as it only relies on the single measurement of current. I have found that a valve voltmeter, especially after much use, requires frequent recalibration, and I should be glad if the author could give any information as to the constancy to be expected from thermo-couples suitable for the measurement of currents of the order of 1 mA and less. On page 601 in connection with the calibration of a receiving system the author states: "If the oscillatory circuit has an effective resistance S, then when in resonance it will reduce the voltage across the terminals of R in the ratio $S/(R+S)$." This is very true and has of course to be taken into account in the application of the method I have described above. The author goes on to say: "Also, by reason of the increase in the effective resistance of the oscillatory circuit from S to $(S+R)$, the voltage amplification of the circuit will be reduced in the ratio $S/(R+S)$." In some methods of measuring signal strength, the resistance R is continuously kept in circuit, so that I do not think the second correction would apply.

Mr. J. Hollingworth (*communicated*): Since the introduction by the author of this method of producing accurate radio-frequency E.M.F.'s, we have made considerable use of it in the Wireless Section of the National Physical Laboratory and have found it of very great value. From the point of view of the practical user it possesses two very great advantages. The first is that, provided proper attention has been paid to the fundamental points in the design, all subsequent calibration is not at radio frequency but consists merely of ordinary Wheatstone-bridge resistance measurements. Consequently the apparatus can be modified and recalibrated in circumstances where there are no facilities for accurate high-frequency measurements. The second is the large range available from a single transformer, especially if not more than 2 or 3 per cent accuracy is required. The effective range of a variable mutual inductance is not usually large, at any rate on the more open portion of the scale, whereas with this system it is possible to retain the same accuracy over a very large range of intensity. In my present signal-measuring apparatus the primary contains two windings with 60 and 30 turns, the latter also being tapped so that altogether 90, 60, 30, 10 or 5 primary turns are available. The secondary is connected across a fixed resistance of 20 ohms divided into 2-ohm and 0·2-ohm sections. With this it has been possible to deal, with the same order of calibration accuracy, with signal intensities ranging from 10 to 17 000 microvolts per metre. As regards the absolute accuracy of the method, a direct check is almost impossible, owing to the difficulty of measuring the small secondary current to an accuracy comparable with that claimed by the system. It can of course be done by increasing both primary and secondary currents until the latter reaches a value which can be dealt with by a thermo-junction of suitable resistance, but in this case the iron-loss factor may become serious. Personally, at any rate for frequencies below about 2×10^5, I prefer to rely on the tests suggested by the author on page 599 and to accept the theoretical values as long as these are satisfied. I have also had the apparatus working at a frequency of 3×10^6, but have not had sufficient experience in this case to give a definite opinion of its working under practical conditions.

Dr. N. W. McLachlan (*communicated*): There is an error in Equation (12) which can be found readily by simplifying (11), when it will be discovered that $(Nm_1)/(Mm_2)$ should read $m_2^2/(2L^2)$. The correct expression for (12) is therefore

$$\frac{I_2^2}{I_1^2} = \frac{M^2}{L^2}\left\{1 - \frac{R^2}{\omega^2 L^2} + \frac{2m_2^2\omega^2}{S^2 + N^2\omega^2}\left(\frac{N}{L} - \frac{m_2^2}{2L^2} - \frac{RS}{\omega^2 L^2}\right)\right\}$$

To reproduce the author's version of Equation (13) it is essential that $N/L - m_2^2/(2L^2) = 0$. Now $m_2^2 = k_2^2 LN$, where k_2 is the coefficient of coupling between the fictitious tertiary circuit and the secondary winding. Making use of this condition we find that $(N/L)(1 - \frac{1}{2}k_2^2) = 0$, or $k_2^2 = 2$, which is only possible if we violate the law of conservation of energy. Since Equation (20) is derived by the aid of (12) and (13) it is clearly erroneous also. Then the derivation of (16) is accomplished by a confusion between mean, root-mean-square, and maximum values. The right-hand side of Equation (16) should read $(di/\pi)(R/\omega L)$, i.e. $\pi/4$ should be replaced by $1/\pi$.* Reverting now to the physical aspect of the problem, the use of a fictitious tertiary circuit may be of assistance mathematically—provided of course that the analysis is free from errors—but I do not think that it is so fundamental as a method based on a loss in the primary circuit. In a transformer having equal numbers of primary and secondary turns, the primary current would exceed the secondary by a small percentage owing to the magnetization loss in the iron necessitated by the ohmic resistance of the secondary. Assuming steady conditions and neglecting radiation, there would be no magnetization of the core if the secondary resistance were zero, and the error would vanish. Moreover, it appears reasonable to base the analytical work on the extra primary current. This is the customary practice pursued by engineers, and it seems to have stood the test of time. Following this procedure, I published a theory of iron-cored high-frequency current transformers more than eight years ago.† When the secondary load is purely resistive the error is—neglecting a term of the second order—given by $R \cos\theta/(\omega L)$ where $\cos\theta$ is the power factor of the primary winding due to the iron alone. In the same publication I discussed the question of loss and low flux density which obtains in these transformers, and from actual data and experiments showed that at low frequencies the error was many times that on high frequencies, since $\mu_a f$ increases with the frequency. Although the influence of capacity in the secondary circuit was omitted, an analysis was made at the time. Since capacity effects are negligible unless the wavelength is very short, publication was thought unnecessary. For example, at 600 m ($f = 5 \times 10^5$ p.p.s.) with

* Corrected for the *Journal*.
† N. W. McLachlan: "Theory of Iron-Cored High-Frequency Transformers," *Electrician*, 1916, vol. 78, p. 382.

a primary of 8 turns and a secondary of 150 on a core of 10-mil stalloy sheets 3 cm^2 cross-section and 10 cm mean diameter, a 0·003 μF condenser across the secondary caused an error of the order of 1 per cent. In dealing with decrement due to the iron, the author refers this to the secondary circuit. The only loss in this circuit is the I^2R of the copper winding, since the secondary magnetization is annulled by that due to the primary balancing current. It seems that the author's mode of viewing the matter is physically incorrect, in spite of its apparent mathematical orthodoxy. Errors due to large resistance and inductance in the secondary circuit have been examined experimentally and analytically in another paper.* My experience with current transformers has been confined chiefly to the measurement of fairly large currents, although some years ago I used them to obtain small voltages across an inductionless resistance in the secondary for purposes of measurement. As this occurred prior to the popular advent of valve amplifiers, the voltages were larger than those quoted by the author. I have recently, however, reverted to the method in measuring amplification. In the construction of current transformers there are several interesting practical points, some of which were cited in a recent article.† When a transformer has to cover a wide range of wave-lengths, it is imperative to design the primary and secondary windings to avoid excessive heating at short wave-lengths. A transformer may be quite cool at 1 500 m, whereas at 600 m it may heat up considerably due to I^2R loss in the secondary arising from increased resistance (the usual frequency effect), and to the proximity of the primary—especially if the turns are close to one another—causing additional eddy-current losses. If this happens, the primary and secondary turns must be decreased to allow a greater copper section on the primary and a less dense field due to the primary, the turns of which should be well away from the secondary. Stranded wire is useful in reducing heating due to this proximity effect. Then there is the problem of relatively small transformation ratio where a wide range has to be covered. For small error on long waves the secondary must have a reasonable number of turns, but in thus accommodating the secondary we should with a small ratio and a large primary current have to use small wire to thread the primary round the core the requisite number of times. This would increase the resistance of the primary circuit and probably cause local heating and reduced aerial current, and these are conditions to be avoided. Such a case can be met by using thin iron of reasonably large apparent permeability, so that the inductance of the secondary can be sufficiently high without having to use too many turns. Thus the factor $R \cos \theta$ in the error term $R \cos \theta/(\omega L)$ would be reduced considerably, since the copper section of the secondary could be augmented. The condition for minimum R/L with given iron and copper sections is that the core shall be circular. An approximation can be obtained by using stampings of different diameters, i.e. stepping the core. In practice, however, a square section will probably meet the requirements. In this country little or no attention has been paid to the commercial production of thin, pure iron or iron alloys of high resistivity. This is possibly due to the lack of interest evinced in iron-cored radio apparatus here, and also to a misconception of the properties of iron at radio frequencies. The thinnest material procurable is 0·25-mm (10 mil) stalloy, whereas in Sweden 2-mil stalloy can be obtained, and in America 1·5-mil pure iron. There are two points about very thin iron which are apt to be overlooked, viz. (1) the space factor, and (2) the cost of manufacture. There is a practical limit to the thinness of insulation between sheets, and this governs the space factor. Thick iron sheets give a small value of inductance at radio frequencies, whereas extremely thin iron means a goodly proportion of insulation, thereby yielding a like result. Thus there must be a happy medium or optimum thickness of metal for any given frequency. This result can be shown quite concisely by mathematical analysis if an elliptical hysteresis loop and a constant permeability throughout the thickness of the plate be assumed. In practice, of course, these conditions are violated. As regards cost, it is clear that, thin iron being more expensive and more difficult to handle, the transformer will be more expensive.

* N. W. McLachlan: "Errors in Iron-Cored High-Frequency Transformers," *Wireless World*, 1917, vol. 5, p. 267.
† N. W. McLachlan: "The Measurement of Aerial Current," *ibid.*, 1924, vol. 15, pp. 273 and 315.

Mr. D. W. Dye (*in reply*): The points raised by Mr. Nancarrow are of great interest and I am glad of the opportunity to amplify and modify the statements made in the paper on account of the special and difficult conditions under which Mr. Nancarrow works. The successful measurement of signal strength when voltages

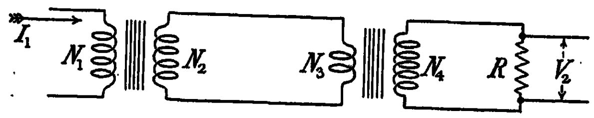

Fig. D.

so exceedingly small as 0·2 μV are involved is a triumph even to a rough degree of accuracy; without a considerable amount of serious experimenting I should not care to suggest any other methods than those Mr. Nancarrow has, doubtless after much painful experience, found to give consistent results. Whilst realizing that it is much easier to make suggestions than to carry them out, it occurs to me that a further extension of my method to the case in which still smaller voltages than those I have mentioned are required would be to use two transformers in cascade. That is, instead of connecting the resistance R of Fig. 3 directly to the transformer secondary, let us interpose another transformer as in Fig. D. If N_3 and N_4 are the primary and secondary respectively of the second transformer, then the equation for V_2 will be

$$V_2 \doteq \frac{N_1 N_3}{N_2 N_4} I_1 R$$

One can then easily step down a further hundredfold by making N_3/N_4 equal to, say, 1/100.

Mr. Nancarrow refers to the measurement of currents as small as 1 mA or less. It is precisely to avoid the necessity of using such small currents that the present

method has been evolved. I do not think that currents less than between 3 and 5 mA can be satisfactorily measured with portable apparatus by means of thermal heaters and vacuum junctions. Even for currents of this order it is necessary to use vacuum thermo-junction heaters of a type similar to those made by the Cambridge Instrument Co. These are chosen so that they may be calibrated with reversed direct current. In a good specimen the galvanometer deflections are not very different on reversal of the current through the heater. The calibration may then very conveniently be made in terms of a Weston miniature-type milliammeter in series with the heater. Such a calibrating arrangement would form a part of the set-up. The correction terms given for the case in which the resistance R is in a frame aerial or other receiving system include the effect produced on the system by the insertion of R in series in it. If this resistance forms a permanent part of the circuit and is included in the term S, then, of course, the correction term will need to be modified. If S is the total resistance including R, then instead of R in any of the equations given we shall write $R\,(1 - R/S)$ and no correction will be necessary on account of change of amplification of the receiving system.

Mr. Ockenden has raised the question of the accuracy of the method described in the paper. I should, I think, assess the overall accuracy at not better than 1 per cent, but I hesitate to commit myself to a definite figure. As far as the transformer itself is concerned, I think that an accuracy of knowledge of the small current to 1 per cent should be attained, if adequate shielding is provided to prevent parasitic currents from flowing through the resistance by reason of capacity. I think that the core loss is of importance, even at the very small inductions at which the iron is worked. The permeability tends to a constant value, and the power factor of the iron may also tend to a constant value since the eddy currents are more and more predominant over the hysteresis losses as the flux density is reduced. The method of using an intermediate current transformer for the purpose of eliminating the parasitic currents appears to be very good. As a result of Mr. Ockenden's remarks I suggested the use of an intermediate transformer as a suitable means of obtaining still smaller voltages such as have been used by Mr. Nancarrow. The scheme outlined in Fig. B has much to recommend it, but for voltages of less than 1 μV it would be necessary to insert the current-measuring device in the primary of the first transformer, which would also need to be of a design capable of giving a constant ratio.

With reference to the apparent error between Equations (11) and (12) to which Dr. McLachlan has referred, I am afraid that the way in which I have arranged these equations is misleading. The results obtained depend upon the place in the development of the equations at which the approximations are made. Intermediate stages were left out between Equations (11) and (12) and it is evident that an apparent inconsistency can be demonstrated, whereas in reality both Equations (12) and (13) are correct. I have set out here my reasoning in a slightly different manner from that which I originally used. Taking, first, Equation (11), we have

$$\frac{I_2^2}{I_1^2} = \frac{M^2\omega^2(N\omega - m_1 m_2\omega/M)^2 + M^2\omega^2 S^2}{L^2\omega^2\left(N\omega - \dfrac{m_2^2\omega}{L} - \dfrac{RS}{L\omega}\right)^2 + L^2\omega^2\left(S + \dfrac{RN}{L}\right)^2} \qquad (a)$$

For the case considered, and from the point of view of corrections which are not very large, we may assume that the coefficient of coupling between the NS circuit and the primary is equal to that between the NS circuit and the secondary. The coefficient of coupling between the primary and secondary may also be considered to be unity. Introducing suffixes to discriminate, for the moment, between the primary and secondary we shall have

$$L_1 L_2 = M^2\,; \quad L_1 N = k^2 m_1^2\,; \quad \text{and} \quad L_2 N = k^2 m_2^2$$

From these we derive that

$$m_1 = m_2 M \quad \text{and} \quad m_1 m_2/M = m_2^2/L$$

Equation (a) above may therefore be written

$$\frac{I_2^2}{I_1^2}\cdot\frac{L^2}{M^2} = \frac{(N\omega - m_2^2\omega/L)^2 + S^2}{\left(N\omega - \dfrac{m_2^2\omega}{L} - \dfrac{RS}{L\omega}\right)^2 + \left(S + \dfrac{RN}{L}\right)^2} \qquad (b)$$

Let $N\omega - m_2^2\omega/L = X$. The right-hand side of (b) becomes

$$\frac{X^2 + S^2}{X^2 - 2X\dfrac{RS}{L\omega} + \dfrac{R^2S^2}{L^2\omega^2} + S^2 + 2RS\dfrac{N}{L} + \dfrac{R^2N^2}{L^2}}\,. \qquad (c)$$

which reduces to

$$\frac{1}{1 + \dfrac{R^2}{L^2\omega^2}\left(\dfrac{S^2 + N^2\omega^2}{S^2 + X^2}\right) + \dfrac{2RS}{L\omega}\left(\dfrac{N\omega - X}{S^2 + X^2}\right)}\,. \qquad (d)$$

Now $N\omega - X = m_2^2\omega/L$; also, for the case under consideration, the coefficient of coupling between the tertiary circuit and the secondary circuit may be considered to be small. As far as corrections are concerned, therefore, we may consider $S^2 + X^2$ as equal to $S^2 + N^2\omega^2$. This gives for (d) the expression

$$\frac{1}{1 + \dfrac{R^2}{L^2\omega^2} + \dfrac{2RSm_2^2}{L^2(S^2 + N^2\omega^2)}}$$

or

$$\frac{I_2^2}{I_1^2} \doteq \frac{M^2}{L^2}\left[1 - \frac{R^2}{L^2\omega^2} - \frac{2m_2^2RS}{L^2(S^2 + N^2\omega^2)}\right]$$

exactly as given in the paper in Equation (13).

The deductions regarding the conservation of energy are of course without meaning, when obtained by consideration of the small differences arising between methods of approximation. The final equation, (20), is therefore not in error in respect of the equations discussed above. With regard to the constant $1/\pi$ in the last term of Equation (20), I regret to find that I made an error in deducing this and that in the advance copies of the paper it was incorrectly given

as $\pi/4$. I am indebted to Dr. McLachlan for pointing this out. The error was really in Equation (15). All the quantities were intended to be root-mean-square values, and the constant (4 in the advance copies) in that equation should therefore have been 2π. Since the square of E_2 enters into the development of the quantity given in the advance copies as $\pi\delta i/4$ in Equation (20), this latter should therefore be multiplied by $4/\pi^2$, giving the quantity $\delta i/\pi$ as stated by Dr. McLachlan. This error, whilst regrettable, was only in a constant and does not in any way invalidate the theory.

I am afraid that I must agree to differ from Dr. McLachlan as to the standpoint from which the losses are viewed. I consider that the representation of the magnetic losses by means of an equivalent tertiary circuit is more fundamental than consideration of them as an increased primary resistance or current. The iron losses do definitely occur in a distributed manner throughout a conductor which is undoubtedly a tertiary circuit, though of a distributed kind. In the theory presented, this circuit is considered to be concentrated and the losses are attributed to it. The losses must, of course, be discussed in relation to the secondary circuit. Apropos of this, however, it would, if otherwise desirable, be just as consistent to consider the effect of the losses from the standpoint of a reduced secondary current as from the more usual standpoint of an increased primary current. My object in introducing this theory of the current transformer was to avoid the necessity of reference to vector diagrams. I am, of course, on controversial ground, but, in common with many others whose opinion I have consulted, I think that, except for quite simple cases, the analytical methods are far more powerful than vectorial ones and enable us to follow in a clear manner the effect of each quantity involved upon the whole. What is needed is, I think, a careful investigation of the change of ratio of transformers when under their normal working conditions in which the flux is extraordinarily small. In my own experiments I have found that the power factor of the iron continually diminishes as the flux density is reduced, and does not show a very definite trend to a constant value at vanishingly small values of B. These experiments are very difficult and I feel that we are working in the dark, especially when dealing with very thin materials such as the 1-mil stalloy to which I have referred.

DISCUSSION ON

"THE PULLING INTO STEP OF A SYNCHRONOUS INDUCTION MOTOR." *

Mr. L. H. A. Carr (*communicated*): The author criticizes the equation of motion of the rotor of a synchronous induction motor †

$$- \rho T_m + T_m \sin \theta + \rho \frac{T_m}{p\omega} \cdot \frac{d\theta}{dt} + \frac{\mathrm{I}}{p} \cdot \frac{d^2\theta}{dt^2} = 0$$

on the grounds that it does not take into account any of the following facts :—

(1) Armature resistance and reactance;
(2) Low-frequency alternating currents in the exciting winding at speeds other than synchronism;
(3) Armature reaction.

To appreciate fully the meaning of the above equation it is necessary to go back to first principles. Any winding when connected to an alternating source of supply will allow to flow in it just sufficient current to produce a flux which, in turn, produces an E.M.F. in the winding of just the right amount to balance the supply E.M.F. (except for the necessary difference to cause that current to overcome the resistance drop). Let the armature winding of a synchronous induction motor be considered and, for simplicity, let the armature resistance and leakage reactance be neglected, so that the internal E.M.F. equals the line E.M.F. at all times. Then at all times the flux will be just sufficient to produce a back E.M.F. equal and opposite to the line E.M.F. When run synchronously, with field excited, the armature will draw from the line only the current corresponding to the difference (either positive or negative) between the M.M.F. produced by the field and the M.M.F. required to produce the necessary flux. If load is put on the machine, within its limits, the current drawn from the line will also include a component in phase with the E.M.F., thus supplying the necessary power. The whole armature current, however, exerts a magnetizing (or demagnetizing) effect, and the current must take up such a phase angle that while the in-phase component yields the necessary power, the vector sum of the field ampere-turns and the armature ampere-turns (the latter being the "armature reaction") gives the required constant value of M.M.F. corresponding to full flux. This is illustrated in Fig. A, where OA represents the flux-producing ampere-turns (F.P.A.T.) and OB the field ampere-turns (F.A.T.).

AB must necessarily represent to scale the armature reaction (A.R.). The circle BCD is the locus of the point B, while θ gives the angle of lag of the centre of the exciting winding behind the centre of the magnetic flux. This diagram can be coupled to a diagram representing the conditions in the electrical circuit, shown in Fig. B. Here PE, parallel to OA, represents the induced E.M.F., the line E.M.F. being PE′ equal and opposite to PE.‡ The relation between the current I in Fig. B and the armature reaction in Fig. A can be determined by reference to Fig. C, which, for simplicity, is drawn for a generator at unity power factor, so that the same arrow-heads and tails represent both E and I. Commencing with the wave of flux (and flux-producing ampere-turns), the induced E.M.F. and currents can be drawn, the arrow, E and I, in line with the centre of the flux wave representing the position on the armature where the induced E.M.F. and also the current reach their maximum. The curve A.R. then represents the magnetic effect of the current I, while F.A.T. represents the total ampere-turns that have to be supplied to the field. It is seen from the diagram that I leads the armature reaction by 90°, and it is so drawn in Fig. B. Referring again to Fig. A, it is seen that the line OG = AB cos ϕ. Since AB is proportional to I, OG is

* Paper by Mr. H. Cotton (see page 211).

† See L. H. A. Carr: "The Pulling into Step of an Induction-Type Synchronous Motor," *Journal I.E.E.*, 1923, vol. 61, p. 692.

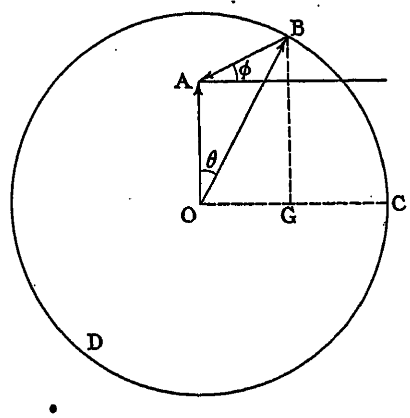

Fig. A.

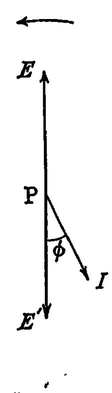

Fig. B.

proportional to $I \cos \phi$, that is to say, OG is proportional to power and, since the machine is synchronous, to torque also. But OG = OB sin θ. That is to say, the torque is proportional to sin θ. In other words the term $T_m \sin \theta$ in the fundamental equation not only allows for armature reaction, but its very existence in that form depends on the fact of armature reaction.

It also follows from Fig. A that the maximum synchronous torque occurs when B has moved to the point C. Here the armature reaction of the in-phase component of current = OC. That is to say, the in-phase component of current equals the armature current that flows on short-circuit with that particular excitation. This fact enables the maximum power and hence T_m to be easily calculated.

If the machine does not move exactly at synchronous speed, slip-frequency currents are induced in the exciting

‡ In this and the succeeding vector diagrams, the convention is adopted that "the sum of the voltages in a circuit is zero"; consequently an impedance drop is represented by $-I(r + jx)$, while an E.M.F. representing a motoring action or absorption of electrical power is in the contrary sense to $I \cos \theta$.

winding. To balance these (so that the flux and consequently the E.M.F. remain the same) equal and opposite currents will be drawn from the line by the armature. The currents produce the "induction motor torque" and the term

$$\rho \frac{T_m}{p\omega} \cdot \frac{d\theta}{dt}$$

represents their action. Consequently the fundamental equation covers this condition also, so that two of the immaterial whether the short-circuit excitation is assumed to be entirely absorbed by armature reaction, or partly by armature reaction and partly by the production of volts lost in impedance, if the test short-circuit curve is used as a basis to calculate T_m. Since reactance causes θ to be smaller for a given torque, the curve of torque against lag of rotor is displaced in a forward direction with reference to a sine wave. This is illustrated in Fig. E, where the sine wave 254 sin θ is compared with the wave-form obtained with a motor

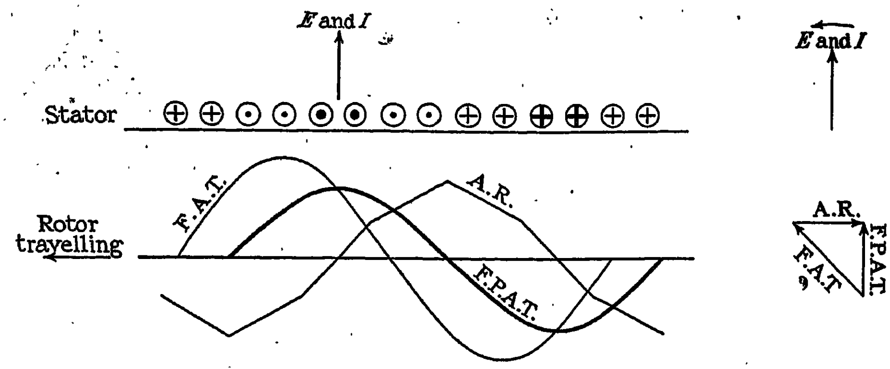

FIG. C.

author's criticisms are unfounded and his "corrections" based on these criticisms are not only unnecessary but are actually wrong.

With reference to armature resistance and leakage reactance, it is admitted that these are not included in the equation. Fig. D is drawn to show the effect of these quantities, and combines both E.M.F. and ampere-turn diagrams, the scales being so chosen that the same

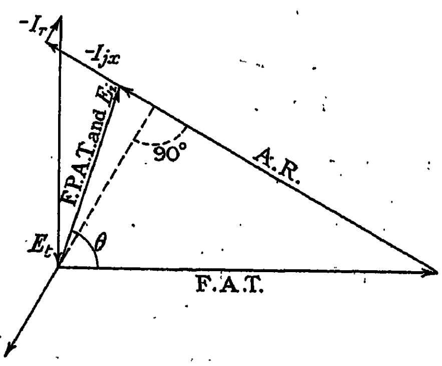

FIG. D.

length of line represents both the internal E.M.F. and the flux-producing ampere-turns on which it is dependent. It is seen that the principal effect of r is to reduce the useful length of E_t, the terminal E.M.F., so that the maximum torque is reduced in the same proportion. The presence of r also slightly modifies the angle θ for any given load. The only effect of x is to reduce the angle θ corresponding to any given torque. The maximum value of $I \cos \phi$ is, as before, the short-circuit value of I for the given excitation, and it is having so much leakage reactance that the maximum torque occurs at $\theta = 77°$, the resistance being neglected. It is seen that, as the machine slips away from $\theta = 0$, the torque is actually greater than in the sinusoidal case, and consequently the motor will synchronize against more torque, rather than less, and consequently

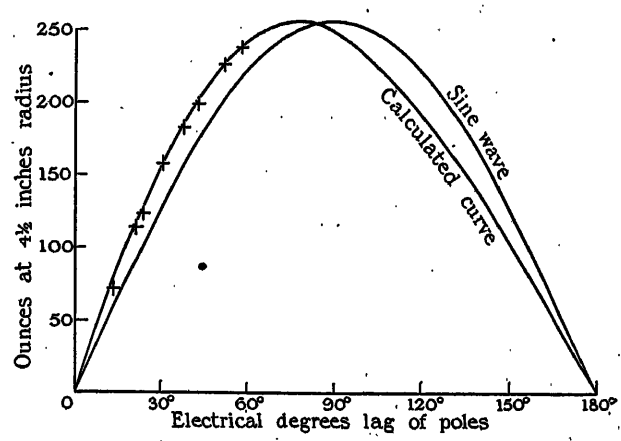

FIG. E.

the error due to reactance tends to cancel out the error due to resistance, and may even overcome it.

Applying the above reasoning to the motor used in the author's experiments, since 10 amperes excitation gives 3 amperes short-circuit current, T_m corresponds to an electrical power of

$$\sqrt{3} \times 245 \times 3 = 1\,270 \text{ watts.}$$

This is equivalent to 1·70 h.p., which corresponds to a torque of 5·95 lb.-ft. or 254 oz. at $4\frac{1}{2}$ in. radius, which

almost exactly agrees with the 258 oz. determined experimentally by the author (see page 215). An attempt was made to reproduce Fig. 4 in the paper by calculation, using the author's value for x the leakage reactance per phase, but the resulting curve was found to rise much more sharply than the test curve. The value of x was therefore examined critically, and consideration shows that the author's value of 40·5 ohms per phase is far too high. The machine is stated to be a 2-h.p. 245-volt three-phase induction motor. If the efficiency is, say, 84 per cent and the power factor 0·82, the full-load current is 5·1 amperes. Yet a reactance of 40·5 ohms per leg, as given by the author, would only allow a maximum current of $245/(\sqrt{3} \times 40{\cdot}5)$ or $3\frac{1}{2}$ amperes to flow on short-circuit as an induction motor, apart entirely from any extra reactance due to the rotor. It would therefore appear that the construction shown in Fig. 5 has broken down for some reason, possibly high rotor-tooth saturation. The points plotted in Fig. 4 (page 214) appear to indicate that θ at pull-out is of the order of 77°, and the author's experimentally determined points are plotted in Fig. E above to show the coincidence with the calculated curve. Even this curve, however, corresponds to a leakage reactance of 9·5 ohms, which is high for a motor of the size in question. To assist in settling this point, it would be of value if the author could give the calculated armature-reaction figure for the machine.

The direct current necessary to balance the polyphase current depends in a cylindrical rotor on whether the direct current splits up in the three phases in the ratio 1, $\frac{1}{2}$, $\frac{1}{2}$, or in the ratio 1, 1, 0. In the former case the exciting amperes to compensate for armature reaction

$$= \frac{2{\cdot}828 \times \text{A.C. amperes} \times \text{Conductors per pole per phase}}{\text{Rotor conductors per pole in series}}$$

In the latter case the constant is 0·866 × 2·828. In either case the number of rotor conductors per pole in series is twice the conductors per pole per phase for a three-phase rotor. Subtracting the resultant figure from the corresponding short-circuit test excitation, the difference would give the excitation corresponding to the internal voltage Ix, from which x could be calculated. Owing to the difference between the two quantities considered being relatively small, the method is, unfortunately, not very exact.

On page 222 the author suggests that the true criterion of synchronizing power should be the minimum exciter capacity and not the slip. In an equation containing several interdependent quantities (which can, nevertheless, be varied within limits by the designer) any one may be chosen as a criterion if desired, but as the full-load excitation is determined by the (synchronous) overload capacity of the machine, it seems wrong to use a variation of this as the criterion of synchronizing power. Although when the machine is built and installed slip is dependent on load, in the design stage that is not so, and, if necessary, the slip can be decreased by increasing the quantity of copper in the exciting winding without seriously affecting the other quantities in the equation. Further, a margin in slip must be allowed for the increase in slip due to the resistance of the leads to the starter and switchgear. The criterion of maximum slip for the required load then appears to be the most suitable practical basis. Again, since it is found in practice that machines are frequently started up by unskilled operators, it is necessary, as a commercial proposition, to ensure that the machines shall always synchronize immediately, that is to say, that they must be capable of synchronizing on the first swing, even if the excitation is switched on at the worst possible position. Consequently this worst position of switching must be used in determining the capacity of the machine to meet the specified requirements.

On pages 223 and 224 the author discusses the agreement between his practical results and his theoretical investigations. Unfortunately these results cannot be compared with the true theoretical equations, since the author's data are conflicting; for example, on page 214 it is stated that $\mathbf{I} = 4{\cdot}32$, while on page 223 $\mathbf{I}$ is said to be 0·135, the same units being apparently used in the two cases. It must be considered, therefore, in view of the foregoing considerations, that the author has failed to prove either theoretically or practically his conclusion (page 224) that "the conditions of operation of a synchronized induction motor during the process of pulling into synchronism are much more severe than they are generally taken to be."

Mr. H. Cotton (*in reply*): I am very glad that Mr. Carr has contributed to the discussion on my paper, because even when the discussion is mainly critical, as in the present case, it adds to the value and interest of the original paper. The most important part of Mr. Carr's criticism is his denial that the armature reaction produces a double-frequency component in the torque created by the motor. To support this he assumes the simplest possible case "so that the internal E.M.F. equals the line E.M.F. at all times." Now the internal E.M.F. (referred to as the back E.M.F. in my paper) is, for a given motor, a function of the speed and the flux per pole, including armature reaction. The speed of a synchronous motor is constant; and, even when it is slipping, the variation in speed is not considerable, so that in the present investigation the back E.M.F. can be assumed to depend on the total flux per pole, and on this only. Hence if the excitation is varied, or if the flux per pole changes because of variations in magnitude of the armature reaction, the back E.M.F. will vary, and the supposition that it is always equal to the line E.M.F. is impossible. Consider now the vector diagram of the motor and assume for simplicity that the armature has zero resistance and that there are no losses, so that the output is equal to the intake. Then since the speed is constant the motor torque is proportional to the intake. In Fig. F, the length OA represents the line E.M.F. per phase, and AB the back E.M.F. per phase. Then OB is the resultant E.M.F., and since we are assuming zero armature resistance the current will lag 90° behind OB, being represented in phase by the direction of OI, and in magnitude by the length of OB. Now OB makes an angle ϕ with the axis OY equal to the external phase angle, and therefore OB represents, with respect to OY, the current in

magnitude and phase. Now torque per phase $\propto$ intake per phase $\propto EI \cos \phi \propto I \cos \phi \propto$ AM, where AM is the projection of AB on to the vertical OZ. The angle θ in the dynamical equation of motion is the angle included between OA and AB; and, as θ varies, the vector AB must rotate about the point A. But the torque of the motor is given by the projection of this vector on to the vertical AZ, and therefore if the torque is to be a pure sinusoidal function of θ, as stated by Mr. Carr, the locus of B must be a circle and therefore the length AB must remain constant. If this is to be the case, then either the armature reaction must be zero, which is absurd, or it must be of constant magnitude and independent of either the magnitude or phase of the current, which is equally absurd. Since the armature reaction varies in magnitude, the increment or decrement of the induced voltage due to it must be variable, and therefore the locus of B is not a circle. Therefore the torque, when expressed as a function of θ, is not a pure sinusoidal function, the departure from this

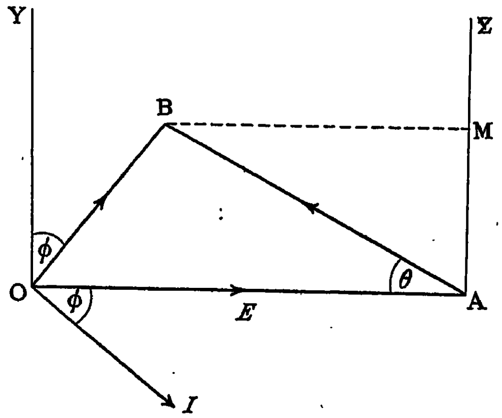

FIG. F.

form being proved in the original paper to be represented by the addition of a sin 2θ term. The solution is not presented as being complete from the point of view of taking all factors into account; it deals only with the most important cause of the departure from the pure sinusoidal form, namely, the direct component of the armature reaction.

I now come to the numerical data derived from the test carried out on the 2-h.p. induction motor. Mr. Carr states that it would be of value if I could give the calculated armature-reaction figure for the machine. It would, but unfortunately I have no design data of any kind for it, otherwise it goes without saying that I should have made a predetermination of the operation of the machine from these data. It is quite possible that the value of 40·5 ohms for the leakage reactance per phase is on the high side. The experimental determination of this quantity can be satisfactorily carried out on a large machine, but it is quite another matter on such a small one, especially when an abnormally large armature reaction has to be allowed for. It was necessary, however, to take the experimentally determined value, since there was no other method of arriving at the figure. The results given in the tables and the analysis indicated by Fig. 5 were the result of carefully made experiments and therefore had to be taken. It is to be expected that, with this type of motor, tests made under abnormal conditions, e.g. open circuit and short-circuit, and operation on wattless current, should give a result somewhat different from the figure for operation under normal conditions. This is stated quite frankly on page 217 of the original paper: it would have been remarkable if there had been a close agreement between the calculated and observed behaviour in such a case. This does not, however, alter the general form of the torque curve as given in Fig. 7. The resultant curve does rise more steeply than a pure sine wave, but whereas the difference between the full-line and dotted curves is only small between $\theta = 0$ and $\theta = 180$, it is very considerable between $\theta = 180°$ and $\theta = 360°$. Therefore, if the motor succeeds in pulling into step before the first unstable position is reached, the effect of armature reaction will be very small, but if it passes this position the large negative torque will produce an increase in slip velocity much greater than would be the case if armature reaction were non-existent. Hence the conditions for pulling into step are more severe than generally supposed when the motor does not pull in between zero and the first unstable position. Surely it was unnecessary to make this qualification in the original paper, because the curves of Fig. 13, which were determined to illustrate this point, were all drawn for a complete revolution of slip. With regard to the unit for the moment of inertia **I**, the experimental determination gave 4·32 lb.-ft. units. When using a dynamical equation of motion it is necessary to use the quantity **I**/g, which is of course 4·32/32, or 0·135, this latter value being used in the equation on page 223.

The final criticism deals with the method of calculating the exciter capacity necessary to enable the motor to pull into step under certain definitely specified conditions. Mr. Carr's objection to the equation developed is obviously the result of his preference for his own method of calculation, as developed in his second paper (*Journal I.E.E.*, 1924, vol. 61, p. 695), which method I criticized on pages 223 and 224 of my paper. The conditions in my method of calculation are that the direct-current excitation is switched on at the angular position $\theta = 0$, and that the slip velocity just comes to zero at the position of unstable equilibrium. This method gives the minimum exciter capacity which will enable the motor to pull into step under the most favourable conditions. It is therefore a definite piece of information. It is perfectly true that the motor may be left to the tender mercies of unskilled attendants, and also that the exciter has another function to perform after the motor has pulled into step, namely, to supply the necessary excitation to give the required pull-out torque and the requisite power factor on stated load. Surely, however, it is very unscientific to try to introduce disturbing factors of this kind into a calculation which has no reference to them. As the title of the paper suggests, the whole of the investigation deals with the phenomena of pulling into step, and not with anything that may take place afterwards. It is quite true that some increase of the exciter capacity as calculated by my method would have to be made,

even for the motor to synchronize in the first swing when operated by unskilled attendants, but the calculation has to be made before the factor of safety can be applied. Now consider Mr. Carr's method of making the calculation. He states in his criticism that the motor must synchronize in the first swing, that is, it must not go past the position of unstable equilibrium. Hence, after excitation, the velocity must decrease from the ordinary induction motor slip at $\theta = 0°$ to zero at the unstable position. Instead, however, of taking the proper value of the slip, he uses a value which is derived from a purely mathematical conception of the problem, which may have no existence in practice at all. It gives, in fact, the worst possible conditions that can exist from the point of view of synchronizing, so that his method and mine give the two extremes between which the exciter capacity must lie, this capacity referring only to the pulling into step of the motor and not to its subsequent operation at synchronous speed. In conclusion, therefore, it will be seen that with the exception of the figure for the leakage reactance, an error in which was unavoidable under the circumstances, Mr. Carr's somewhat extensive criticism is not justified.

INSTITUTION NOTES.

Council's Nominations for Election to the Council.

The following have been nominated by the Council for the vacancies which will occur in the offices of President, Vice-Presidents, Honorary Treasurer, and Ordinary Members of Council on the 30th September, 1925 :—

President. *(One Vacancy.)*

R. A. Chattock.

Vice-Presidents. *(Two Vacancies.)*

Lieut.-Col. K. Edgcumbe, R.E. (T.A.).
Prof. W. M. Thornton, O.B.E., D.Sc.

Honorary Treasurer. *(One Vacancy.)*

P. D. Tuckett.

Ordinary Members of Council.

Members. *(Four Vacancies.)*

Prof. C. L. Fortescue, O.B.E., M.A.
H. Marryat.
R. W. Paul.
S. J. Watson.

Associate Members. *(Three Vacancies.)*

R. Grierson.
Major E. O. Henrici, R.E.
J. W. T. Walsh, M.A., M.Sc.

Associate. *(One Vacancy.)*

E. Leete.

Premiums.

The Council have awarded the following Premiums for papers :—

The Institution Premium (*value* £25).

H. W. Clothier. "Design of Electrical Plant, Control Gear and Connections for Protection against Shock, Fire and Faults."

The Ayrton Premium (*value* £10).

Major E. I. David. "Electricity in Mines."

The Fahie Premium (*value* £10).

Col. T. F. Purves, O.B.E. "The Post Office and Automatic Telephones."

The John Hopkinson Premium (*value* £10).

G. Rogers. "Automatic and Semi-Automatic Mercury-Vapour Rectifier Substations."

The Kelvin Premium (*value* £10).

K. G. Maxwell and A. Monkhouse. "Recent Improvements in the Insulation of Electrical Machinery."

The Paris Premium (*value* £10).

D. Murray. "Speeding up the Telegraphs: A Forecast of the New Telegraphy."

A Premium (*value* £10).

J. D. Cockcroft, R. T. Coe, J. A. Tyacke and Prof. Miles Walker, D.Sc. "An Electric Harmonic Analyser."

A Premium (*value* £5).

S. Holmes. "A Vector Treatment of Long Transmission Lines."

Wireless Section Premiums.

The Duddell Premium (*value* £20).

Major A. G. Lee, M.C., B.Sc., and A. J. Gill, B.Sc. "The Leafield Coupled Arc."

A Premium (value £20).

Capt. H. J. ROUND, M.C., T. L. ECKERSLEY, K. TREMELLEN, and F. C. LUNNON.	"Report on Measurements made on Signal Strength at Great Distances during 1922 and 1923 by an Expedition sent to Australia."

A Premium (value £10).

Prof. E. MALLETT, M.Sc., and A. D. BLUMLEIN, B.Sc.	"A New Method of High-Frequency Resistance Measurement."

A Premium (value £5).

L. C. POCOCK, B.Sc.	"Faithful Reproduction in Radio-Telephony."

The Premiums for papers read before the Students' Sections will be announced later.

Associate Membership Examination Results, April, 1925.

Passed.

Akehurst, A. G. (Southsea).
Bamber, L. J. (Horwich).
Beynon, J. H. (Swansea).
Birtwistle, F. (Bromborough).
Blaquiere, H. A. (Leeds).
Carson, W. N. (Sunderland).
Carter, A. (London).
Cash, H. H. (Bradford).
Causon, G. S. (Margate).
Cotsell, G. W. (Edinburgh).
Davies, C. M. (London).
Fenton-Jones, H. (Folkestone).
Gilbert, J. E. (Birmingham).
Goodall, L. (Stoke-on-Trent).
Hall, W. (Greenock).
Hegazy, H. M. (Wembley).
Hogg, D. B. (Manchester).
Hutchins, P. P. P. (Berkhamsted).
Jackson, F. S. (Halifax).
Jacobi, E. (London).
Jones, L. N. (Wolverhampton).
Lay, F. A. (Stockton-on-Tees).
McCartney, H. (Fenton).
McKinlay, A. (Southampton).
Moore, R. E. (Doncaster).
Overington, L. E. (Ilkley).
Pegg, R. N. (London).
Pizzey, J. H. (Portsmouth).
Prockter, C. E. (Norwich).
Robson, O. L. (London).
Rowbottom, J. R. (Blackpool).
Taylor, H. L. (Rugby).
Turner, V. R. (London).
Verano, E. A. A. (Southsea).
Wales, W. A. (London).
Whitehurst, J. T. (London).
Wicks, P. (Enfield).
Wilson, P. M. (Edinburgh).

Passed Part I only.

Fletcher, C. B. H. (Llanishen).
Hazel, H. (London).
Staygle, E. G. (Worthing).

Passed Part II only.

Aldis, R. F. (Windsor).
Davidson, H. S. (Wolverhampton).
Hoskin, F. (Plymouth).
Shepherd, J. H. (Rawtenstall).
Watkin, H. (Nottingham).
Watson, E. P. (London).

The results relating to candidates who sat for the Examination abroad will be published later.

International Conference on Large Electric Supply Systems.

The Proceedings of the Second Conference, held in 1923, have now been published The volume is entirely in French and comprises 1 200 pages and 400 illustrations. It contains the 50 papers presented at the Conference and full reports of the discussions. The papers cover the practice of 20 different countries in regard to the generation and distribution of electrical energy, and especially porcelain insulators, towers for overhead lines, operation of large transmission lines, outdoor substations, oil circuit-breakers, manufacture and use of high-tension cables, interconnection of networks, earthing the neutral, protection against surges, etc.

Copies can be obtained from the Secretary of the Conference, 25, Boulevard Malesherbes, Paris, at the price of frs. 120 per copy.

The Third Conference is being held at Paris from the 16th to the 25th of this month (June).

International Commission on Illumination.

The Report for the year 1924 of the National Illumination Committee of Great Britain states that the following decisions were agreed upon at the meeting of the above Commission held at Geneva in July 1924 (see *Journal I.E.E.*, 1925, vol. 63, page 66) :—

(1) The International Commission recommended for international adoption as the primary standard of light the brightness of a black body operated under conditions subject to accurate specification, and further recommended that the National Laboratories be asked to take steps—

(*a*) To formulate standard specifications for the construction and operation of the black body as a primary standard of light;

(*b*) To fix upon a definite figure for the brightness as a function of the temperature, of such body expressed in international candles per square centimetre.

(2) A Sub-committee was appointed to draw up a vocabulary dealing with Illumination.

(3) The Commission provisionally recommended certain values for the visibility factor.

(4) The Sub-committee on heterochromatic photometry was asked to include in its work the study of the properties of absorbent screens.

(5) A Sub-committee was appointed for the study of colorimetry.

(6) The following definitions were adopted :—

(*a*) The *Transmission factor* of a body is the ratio of the flux transmitted by the body to the flux incident upon it.

(*b*) The *Absorption factor* of a body is the ratio of the flux absorbed by the body to the flux incident upon it.

(*c*) The *Reflection factor* of a body is the ratio of the flux reflected by the body to the flux incident upon it.

The flux reflected according to the laws of specular reflection is called specularly reflected flux, and the

corresponding reflection factor is called the factor of specular reflection. The flux diffused, i.e. that sent out in directions other than that of specular reflection, gives the diffuse reflection factor. The total reflection factor is obtained by considering the whole of the flux reflected by the body.

(*d*) The *Total flux* of a source is the flux emitted by that source in all directions.

(*e*) The *Upper hemispherical flux* of a source is the flux emitted by that source above the horizontal plane passing through its centre.

(*f*) The *Lower hemispherical flux* of a source is the flux emitted by that source below the horizontal plane passing through its centre.

(*g*) The *Mean spherical intensity* of a source is the average value of the intensity of that source in all directions in space.

(*h*) The *Mean upper hemispherical intensity* of a source is the average value of the intensity of that source in all directions above the horizontal plane passing through its centre.

(*i*) The *Mean lower hemispherical intensity* of a source is the average value of the intensity of that source in all directions below the horizontal plane passing through its centre.

(*j*) The *Mean horizontal intensity* of a source is the average value of the intensity of that source in all directions in the horizontal plane passing through its centre.

(*k*) The *Reduction factor of the mean spherical intensity* of a source is the ratio of the mean spherical intensity to the mean horizontal intensity.

(*l*) The *Efficiency of a source* is the ratio of the total luminous flux emitted to the total power consumed. In the case of an electric lamp it is expressed in lumens per watt. In the case of a source depending upon combustion it may be expressed in lumens per thermal unit per unit of time.

(*m*) The *Visibility factor* for monochromatic radiation is the ratio of the luminous flux to the corresponding energy flux.

The relative visibility factor of a monochromatic radiation is the ratio of the visibility factor of that radiation to the maximum value of the visibility factor.

(*n*) *Brightness*. The brightness in a given direction of a surface emitting light is the quotient of the luminous intensity measured in that direction by the area of this surface projected on a plane perpendicular to the direction considered. The unit of brightness is the candle per unit area of surface.

NOTE.—The above definitions are translated from the official French text. The official English translation will be published later.

(7) The following symbols were adopted :—

Luminous Flux	F	Transmission Ratios	τ
Candle Power	I	Absorption Ratios	α
Illumination	E	Reflection Ratios	ρ
Brightness	B	Visibility Factor	K

(8) It was decided that at the next session a meeting should be devoted to papers and discussion on the art of illumination and the furtherance of good lighting.

(9) It was decided that questions relating to street lighting should be considered at the next session and the National Committees were asked to study the subject and to transmit their communications to the Central Office at the earliest date possible.

(10) The report submitted by the Chairman of the Advisory Committee on the lighting of factories and school buildings was recommended as a basis for regulations or recommendations on the lighting of factories and school buildings.

(11) The National Committees were asked to study the question of glare from motor-car headlights and to send their communications to the Central Office in ample time for the next session.

The following committees have been appointed by the International Commission, the representatives of Great Britain thereon being shown in brackets :—

Heterochromatic Photometry and Colour Screens—(Dr. E. H. Rayner).

Definitions and Symbols—(Mr. J. W. T. Walsh).

Lighting of Factories and Schools—(Mr. L. Gaster).

Motor-car Headlights—(Lt.-Col. K. Edgcumbe).

Colorimetry—(Mr. T. Smith).

It was decided to reduce the annual contribution payable by each country in view of the probable increase in the number of constituent countries. Great Britain will now pay about £77 per annum instead of £113 10s.

A Sectional Committee on Illumination has been formed by the British Engineering Standards Association. The British National Committee forms the nucleus of this Committee, which also includes 12 representatives of Government Departments, manufacturers' Associations and technical Institutions. Five Sub-committees dealing respectively with Photometers, Nomenclature and Symbols, Illumination Glassware, Fittings and Street Lighting have been set up and have held a number of meetings.

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 April–25 May, 1925 :—

	£	s.	d.
Andrew, T. S. (Hebburn-on-Tyne)		10	0
Arman, A. N. (Bromley)		3	6
Badham, L. H. L. (Rugby)		5	0*
Bennett, H. P. (Birmingham)		5	0*
Bennett, T. C. (Wakefield)		15	0
Birmingham and Midland Electrical Engineers' Ball Committee	26	5	0
Boldy, T. D. (Rangoon)		15	0
Broughall, J. A. (London)		5	0
Burrell, F. M. (London)	1	0	0
Bursill, A. (London)		5	0
Carter, F. W. (Rugby)		10	0
Clark, L. J. (Rugby)		5	0
Clifford, A. (Nottingham)		5	0*
Coates, W. A. (Wellington, N.Z.)	1	0	0*
"Conscience Money"		18	6

* Annual Subscriptions.

	£	s.	d.
Dawson, A. E. (Sheffield)		5	0
Donaldson, J. M. (London)	5	0	0
Downie, C. E. (Alloa)		10	0
Elford, A. H. S. (Sutton Coldfield)		2	6*
Ellis, H. S. (Gloucester)	1	1	0*
Eynon, W. (London)		5	0*
Ezard, G. (Leicester)		5	6
Fox, H. C. (Sutton Coldfield)		5	0*
Frazer, W. A. (Belfast)		5	0
Gilliver, S. F. J. (Sale Moor)		5	0
Grey, W. J. (Shanghai)	2	0	0
Hailey, G. (Hong-Kong)		8	6
Harrison, A. J. (London)		2	6
Hayton, T. B. (Lancaster)		5	0
Highfield, J. S. (London)	4	0	0
Higson, W. (Valparaiso)	1	0	0
Hobson, R. S. (Loughborough)		5	0
Hunt, T. C. (Broxbourne)		5	0
Hutchinson, A. P. (Carshalton)		5	0
Jones, C. H. (Colombo)		10	6*
Keeley, D. (Maidstone)		10	6
Lancaster, W. B. (Birmingham)		5	0*

* Annual Subscriptions.

	£	s.	d.
Lang, W. (London)	1	0	0
Main, F. W. (London)		10	0*
Mason, D. M. (London)		5	0
Mather, J. (Stockton-on-Tees)		10	0
Morgan, J. B. (Horsham)	1	15	0
Newburn, E. A. (Rochdale)		5	0
Newton, C. E. (London)	1	1	0
Nicolson, A. M. (Jersey City, U.S.A.) ..	1	1	0
Richardson, W. P. (Birmingham)		5	0
Rushton, A. (London)		15	0
Schofield, H. R. (Manchester)		8	6
Silver, H. C. (New Malden)		5	0
Sparks, C. P. (Surbiton)	35	0	0
Spary, P. G. (Southampton)		10	0
Steel, H. G. (Ilkeston)		5	0
Street, R. W. (Stafford)		5	0
Walmsley, T. (Southport)		5	0
Whitehorn, H. K. (Maidstone)		2	6
Willis, A. H. (Coventry)		2	6*
Wilmot, A. C. (Egham)		5	0
Wolland, G. W. L. (Norwich)		7	6*
Wood, A. N. G. (Leeds)		5	0

* Annual Subscriptions.

THE POST OFFICE AND AUTOMATIC TELEPHONES.

By Colonel T. F. PURVES, O.B.E., Member.

(*Paper first received* 13*th October*, 1924, *and in final form* 4*th February*, 1925; *read before* THE INSTITUTION 5*th March*, *before the* NORTH-WESTERN CENTRE 17*th March*, *before the* NORTH-EASTERN CENTRE 23*rd March*, *and before the* SOUTH MIDLAND CENTRE 1*st April*, 1925.)

SUMMARY OF CONTENTS.

(1) *Introductory.*—The paper attempts to describe points of general interest rather than detail. Absence of automatic aids to manipulation in early telephone switchboards; increasing introduction of such aids as manual systems developed; early automatic systems; the fundamental "Strowger" step-by-step system, and power-driven systems.

(2) *Post Office experience and practice.*—Systems already in use; results obtained; methods of comparing costs; advantageous field of manual and automatic systems.

(3) *The semi-automatic system.*—Claims and objections.

(4) *Layout of telephone areas.*—Economic studies; differences between manual and automatic layout of exchange positions and external lines; subscribers' lines, junction plant, sites and buildings; synthesis of costs.

(5) *Internal plant and wiring.*—Calculation and layout of exchanges; traffic data; grades of service; availability of switches; grading of switching outlets in accordance with theory of probabilities; "artificial traffic," "trunk-hunting" facilities and methods of increasing them.

(6) *Services reserved for manual operating.*—Trunk calls, extra-fee calls, coin-box and call-office traffic; automatic dialling to and from distant exchanges.

(7) *The problem of very large areas.*—Transition difficulties of schemes involving a rigid plan of subscribers' numbers.

(8) *The "panel" system of the American Bell Companies.*—Solution of numbering-scheme difficulties by exchange-code translation; brief description of "panel" system.

(9) *The choice of a system for London.*—Strong attraction of the "panel" system; ultimate adoption of the Automatic Electric Co.'s "director" system; anticipated development in London; agreements for supply of apparatus; standardization of Post Office "step-by-step" automatic system.

(10) *The "director system."*—General description of the system; methods of translation; intercommunication between manual and automatic exchanges during transition period; "key sender" and "call indicator" equipment; the London "mechanical tandem" exchange; various classes of service provided; tone signals; alarms and guarding devices; private branch exchange lines.

(11) *The subscriber's automatic telephone set.*—Standardization of signalling impulses and calling dials; circuit arrangements to avoid high-voltage surges, tinkling of bells, and impulse clicks in receiver.

(12) *Tariffs for automatic systems.*—"Message rate" versus "flat rate"; "time and distance" tariff.

(13) *Progress of automatic exchange construction.*—New exchanges required in London and the provinces; training of staff; output capacity of factories.

(1) INTRODUCTORY.

In the art and practice of telephony the development of means whereby one talking circuit can be connected, at will, with any other has always presented a leading problem, second only to those involved in the actual transmission of speech.

Although its study has been accompanied by a large amount of invention, it is essentially a problem in pure engineering. The object accomplished is one which, in itself, is simple, and the immense amount of effort and ingenuity which has been expended upon it by many hundreds of engineers has been directed wholly to securing its accomplishment at minimum cost in money and time.

The various systems of switching classed as "automatic" perform no new function in telephony; rather do they represent the culmination of a continuous process, in which electrical and mechanical devices have been increasingly utilized, in order to reduce the amount of human effort required to place a telephone subscriber in communication with the correspondent with whom he desires to speak. In this economy of effort the subscriber has shared, and in modern "manual" switching systems the only manipulative act required of him is that he should lift the telephone receiver from its rest before speaking, and replace it when he has finished.

The adoption of the automatic system represents a reversal of this policy of economy of operation, so far as the subscriber is concerned, since it throws upon him the whole of the manipulation required to effect the ordinary local calls which generally constitute the bulk of his transactions, and for that reason the introduction of automatic exchanges in any telephone area is generally a matter of considerable public interest.

The desire of the general public for information is catered for by the daily Press, and, at the other extreme, the professional telephone engineer has at his disposal a great mass of technical literature in many forms, in the multitudinous details of which the electrical engineer who is interested in only a general way may be pardoned for sometimes complaining that he "cannot see the

wood for the trees." I shall therefore endeavour to give a general description of the function of automatic switching apparatus in telephony, with a few main details of the most recent innovations incorporated in the system which is now being installed in new exchanges in London.

The fact that the inception of automatic telephony dates from a time only about three years later than that of the telephone itself, is often overlooked. The electrical telephone was invented—or at least *effectively* invented—in 1876 by Dr. Graham Bell, a native of Edinburgh domiciled in the United States, who was present at a Meeting of the Wireless Section held in the Institution Lecture Theatre in 1921, only about a year before his death.

Although the first telephones were used only for point-to-point communication on private wires, Dr. Bell from the earliest days visualized the use of his invention for general communication among members of the public. In a letter written from Kensington and addressed to the capitalists of the "Electric Telephone Co.," he expressed himself as follows :—

"It is conceivable that cables of telephone wires could be laid underground, or suspended overhead, communicating by branch wires with private dwellings, country houses, shops, factories, etc., etc.; uniting them through the main cable with a central office where the wires could be connected as desired, establishing direct communication between any two places in the city. Such a plan as this, though impracticable at the present moment, will, I firmly believe, be the outcome of the introduction of the telephone to the public. Not only so, but I believe that, in the future, wires will unite the head offices in different cities, and a man in one part of the country may communicate by word of mouth with another in a distant part. Believing, as I do, that such a scheme will be the ultimate result of introducing the telephone to the public, I will impress upon you all the advisability of keeping this end in view."

It has been given to few pioneers in a matter of such magnitude to see their early visions so fully realized. The telephone has indeed provided a notable illustration of the rapid application of scientific discoveries to commercial life and to the home requirements of the people, and this applies with equal force to its most modern developments, such as inductively loaded land and sea cables and thermionic valve repeaters, and coupled wire and wireless transmission, which have so greatly increased the stability and range of communication. In this connection it is noteworthy that the fundamental elements of telephony have undergone only slight modification. The receiver of to-day is almost identical with that of 30 years ago, and the standard transmitter is still the box of carbon granules invented about the same time, while these, in turn, differ only in minor characteristics from the receiver first devised by Dr. Bell and the original carbon transmitter introduced a few years later.

The first exchange switchboard was brought into use at Newhaven, Conn., in 1878 and was equipped with switching apparatus of the "rheostat switch" type, now so well known to wireless amateurs. The limiting possibilities of such apparatus were soon reached and the necessity for the design and manufacture of entirely new types of equipment became evident.

"Plug and cord" exchanges quickly followed. An early switchboard of that type is shown in Fig. 1.* Every operation of signalling and connecting had to be performed by hand. The subscriber had to switch in a generator to call the exchange and had to connect and disconnect his speaking battery by means of another switch. The operator had to restore the shutters of the drop indicators by hand; to connect his speaking set by a plug to the calling line; to plug his generator to the called line and turn the handle; to transfer his speaking set to that line; and, after obtaining a reply, to connect the two lines together by a separate pair of plugs and cord. From time to time he had to reconnect his speaking set and listen, in order to ascertain before severing the connection whether the conversation had been completed.

As the numbers of lines and the amount of traffic increased it was found possible to facilitate the work of the operator by the introduction of such devices as connecting jacks, with auxiliary contact springs for signalling, self-restoring indicators for calling and clearing purposes, and fixed pairs of cords and plugs equipped with pulleys and with ringing and speaking keys which automatically effected all the circuit changes required to send calling signals and to enable the operator to speak and listen on any line. Automatic switching receiver-hooks were also added to the subscribers' telephones.

The increasing size of switchboards made it necessary to employ several operators in one exchange, and the difficulties so introduced were solved by the invention of the multiple switchboard. The British Patent for this was taken out in 1879 by Mr. Scribner, until a few years ago chief engineer of the Western Electric Co. in America, by whom the multiple switchboard was introduced and developed. This notable invention enormously increased the number of lines which could be handled in a single exchange. It enabled the lines to be apportioned in suitable groups to an indefinite number of operators, each of whom answered the calls arising in his particular group and was enabled to complete the connection to any required line in the exchange by means of a compact panel of connecting jacks in which the whole of the lines appeared. Such panels were provided within reach of all operators and every line was multipled to a jack in the same numbered position on every panel of the entire suite. This necessitated the provision of many additional operating aids and refinements, including the simple electrical "engaged" signal which has ever since been a feature of large manual exchanges.

The introduction of the "common battery" system represents another important advance. The first such exchange was opened in Louisville, Kentucky, in 1897; the first in England was opened at Bristol in 1900. The essential feature of the common-battery system is the elimination of batteries from the subscriber's telephone set by the supply of talking current from a large central battery located at the exchange; but the system as launched by the engineers of the American

* Not reproduced in the *Journal*.

Bell Association included a great many new developments of a subsidiary character, among which may be mentioned the use of small electric glow lamps in place of mechanical indicators.

It introduced, for the first time, the use of electrical power to the telephone system, and the current requirements of a large exchange began to be measured in hundreds of amperes instead of in milliamperes. Many types of relays and other electro-mechanical devices were designed and introduced in combinations which greatly extended the automatic signalling and connecting features of exchange working.

Since then the telephone engineers of all the leading nations have participated in the further development of the common-battery system, both as applied to subscribers' lines and to the junction circuits which are required in great numbers in large multi-exchange areas.

The object throughout has been to reduce the cost of giving a rapid and reliable service, by simplifying in every possible way the operations of the telephonist in handling calls. Such savings affect the engineering and other costs as well as the service operating costs. If we assume that the introduction of a certain amount of automatic aid to the operator results in halving the amount of time taken to deal with a call, not only is the effect to double the average number of lines which an operator can handle, and so reduce the number of operators by half, but the costly multiple switchboard suites will also be reduced to half the previous length, the necessary dimensions of switch-rooms and operating-staff accommodation rooms will likewise be halved and a large economy effected in the cost of sites and buildings.

The amount of assistance given to the operators in all modern manual exchanges, by the introduction of automatic devices, is very great. In the case of some of the small telephone companies in the United States, where the whole service is given from a single exchange at a "flat rate" charge, it has been possible to combine these devices in such a way that the normal manipulative action of the operator is reduced to the mere insertion and withdrawal of a single plug for each communication effected. The call is indicated by the glowing of a lamp adjacent to a particular plug. When the operator lifts the plug, her speaking set is automatically connected to the line and the number of the called party is ascertained. The insertion of the plug in the jack of the wanted line automatically disconnects the operator's speaking set and connects a periodic ringing machine to the line. When the called subscriber lifts his receiver to reply he actuates a trip magnet which disconnects the ringing machine and places the two parties in communication. The replacement of the receivers at the end of the conversation sends a clearing signal, on observing which the operator withdraws the connecting plug. With so simple a manipulative system the number of calls which an operator can normally deal with in an hour is naturally very high.

Side by side with the foregoing development of so-called "manual" systems many inventors and engineers have been devoting their attention to the devising of purely automatic systems in which the intervention of an operator in connection with ordinary local calls is entirely dispensed with.

Probably the first recorded proposal for an automatic system is that of Connolly,' which is covered by the joint patent of Messrs. M. D. and T. A. Connolly and T. J. McTighe, United States Patent 22458, dated 9th December, 1879. This system bears a remarkable resemblance to the Wheatstone "ABC" dial telegraph, and although the Patent refers to a system of 100 lines the drawings associated with it only illustrate one of 25 lines. The face of the dial was marked with letters, each of which represented one subscriber on the system.

The first really important development of automatic telephony is represented by the inventions of Mr. Strowger, whose name was destined to become universally known as its pioneer. Strowger's first patent is dated 10th March, 1891, United States Patent No. 447918. This early system required five wires between

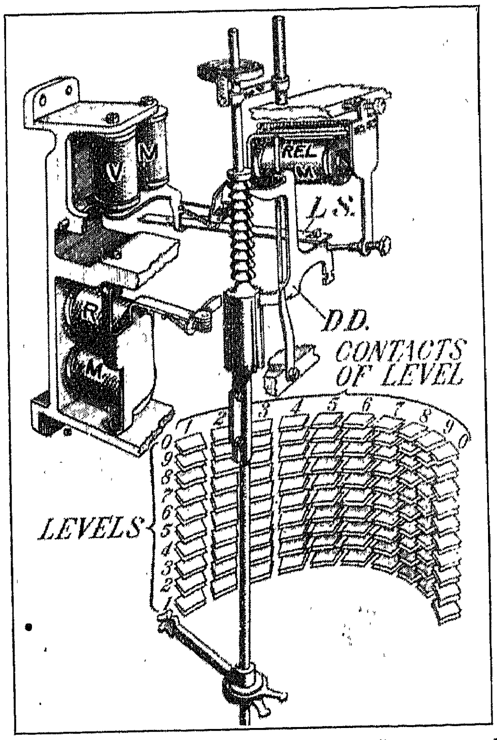

FIG. 2.—Diagram illustrating working of Strowger selector.

each subscriber's station and the exchange. Subsequent improvements enabled the number of wires to be reduced to two, which brought the system into line with standard telephone engineering practice and led to its fairly extensive adoption among the smaller telephone companies in America and elsewhere.

The Strowger system is the basis of what is known as "step by step" automatic telephony, and at the present day there are more automatic telephones served by exchanges of that type than by any other. Its fundamental idea is the simple one of straight decimal selection, digit by digit, in a forward direction. Fig. 2 gives a diagrammatic view of the well-known Strowger selector switch. It consists essentially of a set of insulated contact brushes, or wipers, with means for bringing them into connection with any one of 100 sets

of contacts, 10 of which are placed side by side, in the arc of a circle, on each of 10 levels. The brushes are carried on a vertical spindle to which step-by-step vertical movement and rotation can be imparted by means of electromagnets actuated by the trains of signalling impulses produced by the calling dial of the subscriber's telephone. The brushes rest normally slightly below, and to the left-hand side of, the banks of contacts, being held in that position by gravity and by means of a spiral spring, shown at the top of the figure, which acts upon the spindle. Impulses in the vertical magnet (VM) step up the brushes to a position

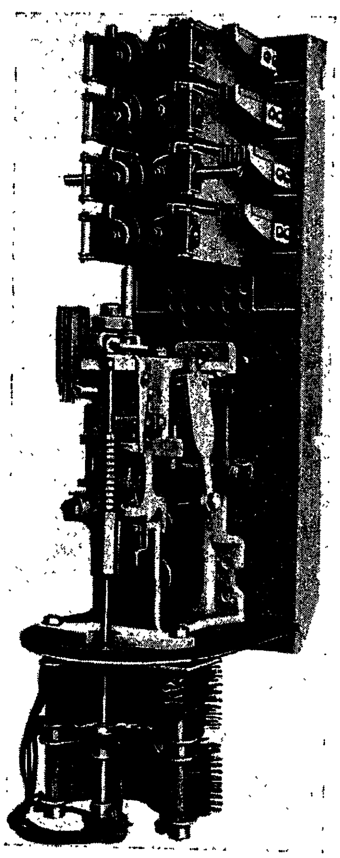

FIG. 3.—Strowger selector.

opposite any required level by means of a pawl which engages with a vertical ratchet on the spindle. A subsequent train of impulses in the rotary magnet (RM) will cause the brushes to enter the bank of contacts on that level and will rotate them into connection with any desired set of contacts, representing the line of the called subscriber, by means of a pawl and horizontal ratchet. So long as the connection is required the vertical and horizontal ratchets of the spindle are engaged by a double detent (DD) which locks it in position. When the calling subscriber restores his receiver on the completion of conversation, a release magnet (Rel.M) is actuated and disengages the double detent; the spiral spring then restores the brushes to a position horizontally clear of the contacts bank, and the spindle and wipers drop by gravity to the normal position of rest.

The foregoing description applies to the operation of the final selector switch of 100 lines, which completes the connection to the called subscriber and is governed by the impulses representing the tens and units digits.

In order to effect the selections represented by the hundreds, thousands, and other digits, a switch of the same general design is employed, but the digit impulses are utilized to govern only the vertical selection of a level of 10 contacts, all of which are connected to further selector switches instead of to the actual subscribers' lines. In this case the function of the rotary magnet and of the horizontal movement of the brushes within the bank of contacts, is known as "trunk hunting"; the brushes are driven rapidly forward by local impulses until they find, and come to rest upon, a set of contacts connected with an *idle* selector in the next rank of switches, which will receive, and deal with, the next train of digit impulses sent in by the calling subscriber. The bank contacts of all ranks of switches are multipled together in groups, in a manner analogous to the multipling of subscribers' and junction lines at a manual exchange.

Fig. 3 gives a view of a final selector switch of present-day pattern, without its protective cover. It will be seen that in addition to the double brush and bank contacts carrying the talking-circuit connections, a separate brush and set of bank contacts—known as the "private bank"—is also provided. The latter carry a third conductor used for preventing the making of connections with engaged lines or switches, a function similar to that of the third or "sleeve" conductor used in the plugs and cords of manual exchanges. The eight relays shown at the top of the figure control the circuit re-arrangements associated with each step of the operation of the selecting mechanism, and perform other necessary duties which, *inter alia*, enable the switch :—

- To ascertain whether the wanted line is disengaged, and, if not,
- To transmit a "busy" signal to the calling subscriber;
- To provide against interruption by other calls for the same line;
- To disconnect the called line from its call-receiving equipment;
- To ring the wanted subscriber;
- To disconnect the ringer, join the circuit through, and operate the caller's meter when the called subscriber has replied;
- To supply talking current;
- To release the connections when conversation has finished.

In early Strowger exchanges it was necessary to provide a selector switch for every subscriber's line, the line being connected to the brushes and finding its outlets via the banks of multipled contacts. This practice involved the use of a very large number of these comparatively expensive pieces of mechanism, each of which was utilized, on the average, for only a very short time daily. Great economic advantage therefore resulted from the invention in 1907 by Mr.

Alexander Keith, one of the engineers of the Automatic Electric Co. of Chicago, of a simple form of line switch, which took the place of the selector on the subscriber's line, and connected the line to an idle selector in a common group before the operation of dialling impulses began. The use of the Keith line switch thus enabled the number of selector switches in an exchange to be very much reduced and to be proportioned in accordance with the total traffic to be carried, without regard to the number of subscribers' lines connected. The Keith switch has recently been superseded by a simple form of rotary line switch which serves the same purpose.

Although the Strowger step-by-step system, with many variants, has reached a high state of development in many lands, it is very far from holding the field alone. Its basic principle of straightforward decimal selection of circuits in comparatively small groups, although simple both in theory and in practice, undoubtedly tends to multiplicity of switches. The fact that all the motions of its parts are energized by the attraction of the armatures of electromagnets has also appeared to some highly competent authorities to be a weakness.

The development of forms of automatic exchanges in which the motive power of all the main elements is derived directly from a power motor has therefore received much attention and has attracted the efforts of many exceedingly able inventors and engineers. The earliest achievements in that direction are marked by the names of E. A. Faller, the Lorimer brothers, and F. R. McBerty. Faller was responsible for United States Patent 686892 of the 19th November, 1901, which provides for the use of "well-designed mechanism performing a definite cycle of operations and driven by some source of power." He also provided at the subscriber's telephone a calling device which enabled the required number to be visibly set up before any impulses were transmitted over the line.

Both these features were adopted in the Lorimer system, which had its origin in Canada and was installed in two public exchanges—Brantford and Peterborough—in Ontario. It was one of the first systems to be tried by the British Post Office and was installed in 1914 at the Hereford exchange, where it is still giving good service. Although the manufacture of this system for new installations has apparently now been abandoned, it contributed important ideas to the general subject.

The principle of power-driven machine-switching has been further developed by the Western Electric Co., in association with the American Bell telephone organization, in two forms known as the "rotary system" and the "panel system." These two systems differ widely from each other in mechanical design, but are electrically analogous. The rotary system, devised by Mr. McBerty, was installed experimentally in the company's New York factory in 1910, but the subsequent development and ultimate adoption by the Bell organization of the panel system, to which fuller reference will be made later, led to the abandonment of manufacture of the rotary system in the United States, where it has not been installed in any public exchange. Its manufacture was transferred to the Western Electric Co.'s factory in Antwerp, and it has been adopted with success in many European and other cities. The system, which is in operation in the Post Office exchanges at Darlington and Dudley, is undoubtedly an excellent one.

(2) Post Office Experience and Practice.

For more than 15 years the Post Office has studied the development of automatic exchanges very closely. In the early stages it adopted the policy of giving an actual working trial to such systems as promised to be capable of providing good and reliable public service.

The exchanges which it has, so far, installed are as follows:—

Exchange	*System*	*Opened*
Headquarters Official	Automatic Electric Co. (step-by step)	1912
Epsom	,, ,,	1912
Hereford	Canadian Machine Telephone Co. (Lorimer)	1914
Darlington	Western Electric Co. (rotary)	1914
Accrington	Automatic Telephone Mfg. Co. (step-by-step)	1915
Newport (Mon.)	,, ,,	1915
Chepstow	,, ,,	1915
Portsmouth	,, ,,	1916
Paisley	,, ,,	1916
Dudley	Western Electric Co. (rotary)	1916
Blackburn	Automatic Telephone Mfg. Co. (step-by-step)	1916
Leeds	,, ,,	1918
Grimsby	Siemens Bros. (step-by-step)	1918
Stockport	,, ,,	1919
Ramsey	Siemens Bros. (village)	1921
Hurley	,, ,,	1921
Fleetwood	Relay Automatic Co.	1922
Southampton	Siemens Bros. (step-by-step)	1923
Swansea	,, ,,	1924
Sketty	,, ,,	1924
Dundee	Peel Conner: North Electric Co. (step-by-step)	1924
Broughty Ferry	,, ,,	1924
Marton	Automatic Telephone Mfg. Co. (village)	1924
York	Auto. Tel. Mfg. Co. (step-by-step)	1924
Hadleigh	P.O. (Rural Auto. System)	1924
Blockley	,, ,,	1924

In some of these cases installation was seriously delayed by the war. The behaviour and the running expenses of all the exchanges mentioned have been critically watched and it may be mentioned that in no case has there been reason to regret the selection of any of the systems for installation. All have given, and continue to give, good service at reasonable maintenance cost.

It was also proved that the automatic method of working was generally acceptable to the British public and that the linking up of the automatic plant with the manually operated switchboards, required at all exchanges for toll junction and trunk traffic, could be effected satisfactorily.

The first exchanges of each type were installed, for the sake of experience, at places where new switchboards were needed, and it was quite recognized that some of them would operate under conditions which would not enable the automatic system to produce its best economic results in comparison with the cost of manual service. This arose mainly from the need for associating with each automatic exchange an unduly large proportion of manual switchboards for the purpose of dealing with external traffic. Much of this traffic fell within the unit-fee area and would, in a fully equipped area system, have been disposed of by automatic means. The total expenses were, in some cases, found to be somewhat higher than those which would have resulted from the use of manual exchanges, but they provided data by means of which financial comparisons could be made between the economic results to be anticipated in multi-office unit-fee areas fully equipped with the automatic or with the manual system. Such comparisons are made on the basis of inclusive annual costs, taking into account interest on capital, depreciation, maintenance and operating, with a calculated proportion of commercial and overhead charges. Many typical areas were studied in this way and the results were generally favourable to the full equipment of the area with automatic plant. In the Sheffield and Newcastle areas, for example, savings of over £14 000 a year and of nearly £7 000 a year respectively were indicated. After the various factors entering into these calculations had been investigated, it was found that the policy of providing automatic or manual equipment could in many cases be determined, without detailed calculation, by the application of the following general principles :—

(1) In an area where the anticipated development on all exchanges in a period of 20 years does not exceed 1 000 subscribers' lines, manual equipment is to be provided.
(2) In all other cases automatic equipment is to be installed, provided that the following traffic conditions obtain :—
    (*a*) The "calling rate" to average not less than 1·2 calls per subscriber in the busy hour of the day.
    (*b*) The proportion of local traffic to be not less than 70 per cent.
    (*c*) The number of manual operators' positions required, in association with the automatic exchange, not to exceed 55 per cent of the number of positions required for a manual system.

The fulfilment of conditions (*a*), (*b*) and (*c*) provides a safe case for the adoption of the automatic system. Cases which fail to satisfy these conditions are treated as border-line cases and are subjected to detailed calculation. The result of the investigation of these doubtful cases has, so far, shown that in more than 80 per cent of them the automatic system represents an economy.

Appendix 1 shows the results of the calculations made up to a 10-years period in three such border-line cases : Keighley, Maidstone and Macclesfield. Experience has shown that there are few areas, where the 10-years' development will reach or exceed 2 000 subscribers' lines, in which the automatic system will not show a comparative saving, and, as a result, it has just been decided that it is safe to install the automatic system, without detailed financial comparison with manual, if the following conditions will be satisfied within that period :—

(1) The average subscriber's calling rate to be not less than 5 calls per day.
(2) The number of local calls switched automatically to be not less than 4 000 per day.
(3) The proportion of originated calls requiring to be handled manually to be not more than 40 per cent.

On the other hand, if the number of local calls which might be switched automatically will not exceed 3 000 per day within the 10 years' period, manual equipment will be installed without question.

The introduction of the automatic system does not necessarily involve any appreciable modification of the private branch exchange switchboards working in the area. A great many private automatic exchanges have nevertheless been installed by the Post Office to meet the wishes of its subscribers. Some of these exchanges provide for over 500 lines. The majority of them are of the Relay Automatic Telephone Co.'s type.

(3) The Semi-automatic System.

Many telephone authorities, while constrained by the force of facts to admit that automatic selecting and switching mechanisms had been shown to be capable of furnishing reliable and economical service, yet hesitated to entrust the means of operating them to the general body of subscribers. It was argued that personal communication with an operator was necessary in order to reassure the public and to ensure proper use of the plant. To meet this frame of mind several systems known as "semi-automatic" have been introduced. These utilize the complete mechanical switching equipment of a full automatic exchange, in addition to a suite of manual switchboards, the operators at which receive all calls through the medium of an automatic "traffic distributor," ascertain the required connections verbally, and manipulate impulsing keyboards which steer the connection through the automatic selecting switches to the desired line. The subscriber is provided with an ordinary common-battery telephone set, and his procedure may be identical with that of a manual exchange system.

In effect, the semi-automatic system carries to its extreme the principle of reducing the work of the operator to a minimum, and its economic justification, as compared with manual systems, mainly depends upon the very high traffic load which it enables an operator to carry without strain. In addition, the cost of training operators is somewhat reduced and the setting up and severance of connections are effected more rapidly.

Its claims to superiority over the full automatic system are mainly based upon the simplicity of the subscribers' apparatus and procedure, the personal supervision of each call by an operator, the generation

of signalling impulses by easily maintained mechanism at the exchange, and restriction of the transmission of these impulses to circuits which are either within the exchange or are carried to other exchanges over junction circuits which are likely to be in more perfect condition than the subscribers' lines. All these claims are valid, so far as they go. It is also true that, from a service standpoint, it is much easier to introduce semi-automatic than full automatic in substitution for the manual system, especially in a multi-office area. There is no need to make wholesale changes in the subscribers' numbers or in the names of exchanges, or to worry subscribers by troublesome alterations in directories and working instructions, as the various exchanges in the area are successively converted to the automatic system. So great and so real did these difficulties appear that many convinced advocates of the full automatic system recommended the adoption of semi-automatic as an interim system during the long period of years that must elapse in an extensive telephone area before all its exchanges are transformed, notwithstanding the large wastage of distinctively semi-automatic equipment which must necessarily take place when full automatic working is finally introduced in the area as a whole.

A few years ago the Post Office was seriously considering the installation of one or more semi-automatic exchanges, mainly with a view to gaining experience which would be useful in connection with the treatment of very large areas such as London, and endeavours were being made, in association with contracting companies, to develop a system embodying the following prescribed features :—

(1) Standard manual-exchange operating supervision for all classes of calls.
(2) Control and release of all connections to be vested in the operator.
(3) Manual registration of successful calls.
(4) Even distribution of calls to operators in a regular indicated sequence; no waiting traffic to be hidden.
(5) Automatic team work and traffic concentration facilities to be provided.
(6) Facilities to be provided for holding switching plant for observation when faulty connections are established.
(7) Facilities to be provided for transferring special calls to separate positions for completion.
(8) Automatic selection of outgoing junction circuits for non-fee junction calls.

The quantity and complexity of equipment required to furnish the service and traffic facilities stipulated are, on a semi-automatic basis, considerably greater than are necessary for the full automatic system, and both the capital and the annual costs are higher. After careful study and valuation of all the pros and cons, the Post Office Engineering Department has reached the conclusion that, in general, when a change from manual working is justified, the full automatic system presents a greater balance of advantage than the semi-automatic.

As regards the interim use of the latter to overcome the special difficulties of introducing full automatic in large multi-office areas, recent inventions have, as described later, indicated a way out of these difficulties which permits of direct conversion, exchange by exchange, without any need for utilizing the semi-automatic system as a stepping-stone.

(4) Layout of Exchange Positions and External Lines.

The determination of the most economical number and location of exchanges to serve a telephone area involves an exhaustive study of all the costs of providing and maintaining external and internal plant and buildings, and also the cost of operating the plant. This is necessarily prefaced by development studies of all parts of the area, and general traffic estimates, extending many years ahead. Comparison of the costs of alternative schemes is made on the basis of annual charges, capital cost being converted into interest and depreciation and added to the direct annual costs of maintenance and operation.

The main items of cost to be considered in designing the layout are represented by :—Subscribers' lines, junction circuits, exchange buildings, equipment and power plant, "A" (answering) operators, "B" (junction) operators.

An increase in the number of exchanges reduces the area to be served by each of them, and consequently reduces the cost of subscribers' lines, both by shortening their average length and by enabling standard transmission efficiency to be attained by the use of a lighter gauge of copper wire. On the other hand, it increases the requirements for junction circuits, buildings and power plant. The optimum number of exchanges is represented by the layout which reduces the summation of all these costs to a minimum.

The number of exchanges required for the most economical service of an area on the automatic system differs materially from that required for the service of the same area on the manual system.

The main reason for this is the fact that junction circuits can be provided much more freely in an automatic system, since they do not carry with them the heavy operating costs which accompany their use in a manual system. In the automatic case only the plant costs of the junction system come into the calculation, and fuller advantage can therefore be taken of the economies represented by shortening the subscribers' lines. As a consequence, the adoption of automatic service in any large area generally involves an increase in the number of exchanges and a reduction in their average capacity.

The foregoing does not apply to portions of an area in which the telephonic density is such that exchanges of 10 000 lines' capacity are justified under either system. This number of lines happens to represent the practical limiting capacity of both manual and automatic exchange units, the limit in the manual case being the maximum number of connecting points which an operator is physically able to reach, and in the automatic case the decimal limit of the number of lines ever required at one point. The theoretical locations of exchanges in a dense city area are therefore the same for both systems.

In either case two or more 10 000-line units are housed in the same building if convenience so dictates.

The economies in line plant that can be realized in a properly laid-out automatic system, as compared with a good layout on a manual basis, are considerable. Calculations made about three years ago in connection with the layout of the London area showed that the costs of the line plant for the automatic system, at or about the year 1945, would be nearly 30 per cent below those of a manual system.

In the matter of exchange buildings the automatic system also enjoys a certain advantage. Accommodation for operators is not required at many of the smaller exchanges, while at larger centres, where provision is made for inquiries and certain classes of traffic to be dealt with by operators, the amount of such accommodation required is comparatively small. The plant serving a given number of lines can therefore be housed in smaller and cheaper buildings. This advantage is partly discounted by the fact that the average number of lines per exchange is less in the automatic system, and more buildings are required than would be the case in a manual layout. In general, the cost per line of small buildings is greater than that of larger buildings, but it is found that the automatic system introduces an overall economy of about 13 per cent in the cost of exchange sites and buildings. The total economy in external line plant, sites and buildings, which may be credited to the automatic system is about 23 per cent as compared with the manual system.

Reduction in the size of exchanges below a critical figure of about 3 000 lines also increases to a certain extent the cost per line of power plant and of automatic switching equipment for handling a given amount of traffic. These factors therefore tend, so far as they go, to keep up the size of exchanges of smaller capacity than 3 000 lines. In this respect automatic conditions differ markedly from those of the manual system, in which the high cost of the multiple equipment and its cabling causes the cost of exchanges, per line, to increase very rapidly with their size; this increase is, of course, much more than counterbalanced by the economies in junction working which attend the gathering up of the lines into large exchange groups.

The methods of calculation adopted in determining the layout of automatic exchange areas can be referred to only briefly.

The telephone system in this country is laid out in local fee areas covering all territory within a radius of 5 miles of a main exchange, with the exception of some of the largest towns which have a greater radius, up to 10 miles in the case of London. It is usual to consider the layout for one of these areas as a whole, but in making a detailed study the area has, of course, to be divided up into small portions, each covering the maximum territory that might be served from one exchange. The costs of serving this portion from one, two or more exchanges are then calculated, and the most economical arrangement ascertained.

In order to calculate quickly the economical layout of various telephone areas it is first necessary to prepare graphs showing the cost variation of each of the following items for different sizes of exchange :—

(a) Subscribers' lines.
(b) Junctions to carry traffic which would be created by increasing the number of exchanges serving each portion of the area, as explained above (these will be referred to later as "local junctions").
(c) Junctions to other exchanges, in so far as they vary with the size of exchange.
(d) Building and power plant.

Other costs, such as that of subscribers' instruments, are independent of the size of exchange and therefore do not enter into the calculation.

In applying these factors to the problem of determining the most economical size of exchange in areas of various densities, they are all expressed in the form

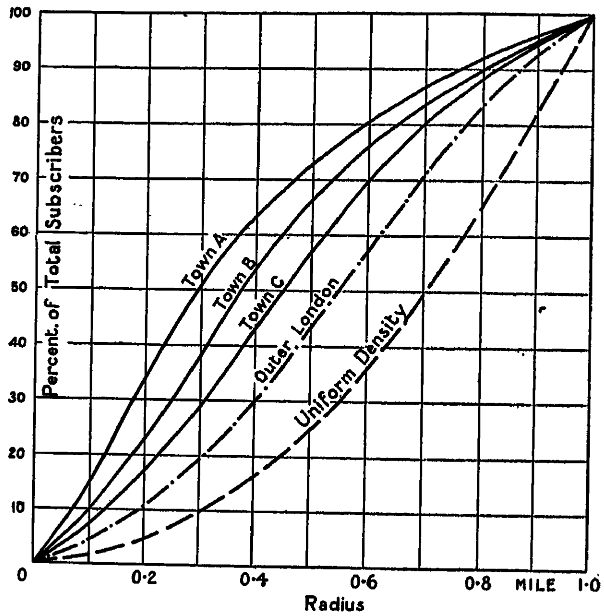

FIG. 4.—Number of subscribers within various radii, shown as percentage of subscribers within 1 mile radius.

of annual cost per subscriber's line and plotted against the size of exchange.

The calculation of the cost of the subscribers' line plant is somewhat complicated, but certain approximations can be made which simplify the work considerably. To determine the basic costs involves numerous calculations of the capital costs of various cable routes comprising different types of cable and different numbers of ducts laid under all classes of roads, with additions for overcoming difficulties depending on the particular locality being considered. From these and investigations into the lives of the various components of the plant, the interest and depreciation charges are derived. An allowance for maintenance is then added, giving the total annual cost per mile of each type of circuit. Fig. 4 shows the distribution of subscribers in a few typical cases, expressed as percentages of the total within a 1-mile radius of the exchange. The curve for "uniform density," which is of course the simple geometrical curve representing increase of area, gives

the largest percentage of subscribers in the outer portions of the area and represents one extreme condition. The nearest approach in practice to uniform distribution is found in the central districts of large cities. The curve for the districts of outer London, which is also shown, approaches more closely to the curves for smaller cities. The other curves represent towns in which the density diminishes, in various degrees, from the centre outwards. The curve most nearly representative of the area being studied is taken.

From this graph, curves are prepared showing the average length of subscribers' lines within any maximum radius, due allowance being made for the difference between route mileage and radial mileage. Owing to the fact that the cable routes have to follow the lines of streets, the route distance is much in excess of the radial, and generally the ratio is highest for the lines nearest to the exchange. From an analysis of a large number of exchange areas an average ratio of

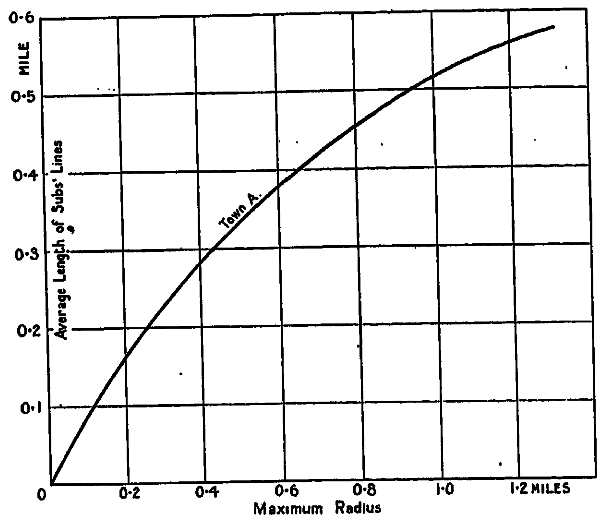

FIG. 5.—Average lengths of subscribers' lines within various radii.

route to radial measurement at various distances from the exchange has been arrived at and is used for working purposes.

Fig. 5 shows as an example the curve for an area similar to town A of the previous figure. From such curves and the cable cost per mile, the average cost per subscriber's line is ascertained.

The number of junctions required depends upon the traffic, which can be estimated from records of the traffic under existing conditions, and upon the number and methods of connecting the outlets from selector switches used in the switching system adopted. In estimating the cost of these junctions due allowance must be made for the various gauges of conductor necessary to give the required transmission efficiency, and for loading where this proves more economical than the provision of heavy conductors; the limits of resistance imposed by switching and signalling requirements have also to be taken into account. Detailed capital costs have been estimated for each of the types of cable necessary, and the annual costs per mile of circuit have been arrived at as described previously. In this manner a curve showing cost of junctions against size of exchanges for any particular area can be prepared.

Fig. 6 shows combined building and power plant costs based on statistics of a large number of existing exchange buildings. It has been necessary to ascertain

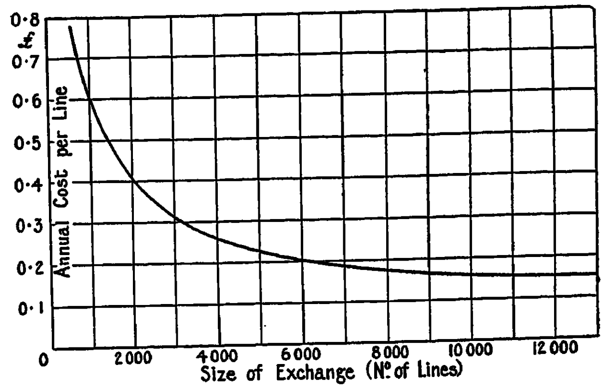

FIG. 6.—Annual cost of automatic exchange buildings.

capital costs of sites and of buildings specially designed for automatic exchanges, with all incidental accommodation. On this the interest and depreciation are calculated, and the charges for maintenance, cleaning, heating, etc., are added.

The annual charges for the power plant are arrived at in a similar way. For automatic exchanges over

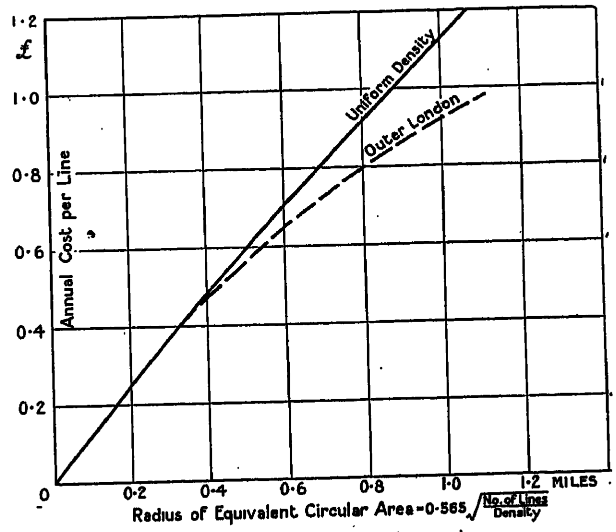

FIG. 7.—Annual cost of lines in various areas.

about 3 000 lines the cost of power plant, maintenance, etc., is practically the same per line; but as the size of exchange decreases, this cost increases, as already mentioned. Hence the 3 000-line exchange is taken as a datum point and only the excess cost for exchanges of smaller capacity is brought into the graph. The curve shows that the accommodation cost for exchanges of 1 000 lines is about 12s. per line per annum, reducing to below 4s. per line in the case of the largest exchanges.

The first step preparatory to dealing with the layout of an exchange area is to have a detailed development study made of the whole area to ascertain the number of subscribers likely to be obtained in the future, and their distribution. The Post Office practice is to have

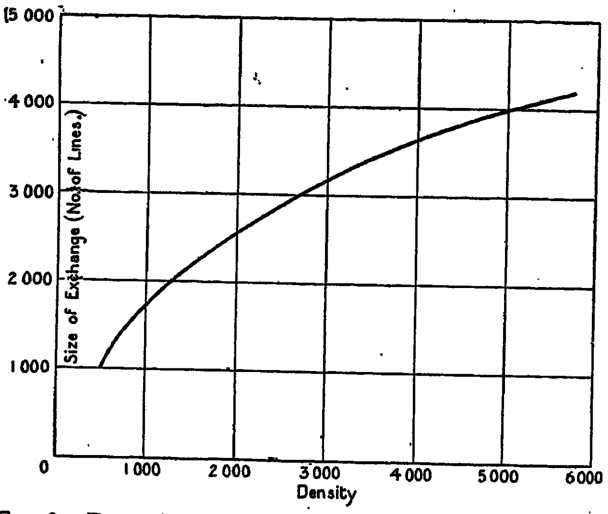

FIG. 8.—Economical sizes of exchanges for various densities.

these forecasts plotted on plans to show the number of subscribers anticipated in each small portion of the area, say in sixteenths of a square mile, at 5, 10, 15 and 20 years ahead. In the case of an ordinary provincial town an inspection of this plan shows that there is always a fairly definite business centre where the telephonic density is high, falling off rapidly towards the suburbs. This condition calls for a large exchange

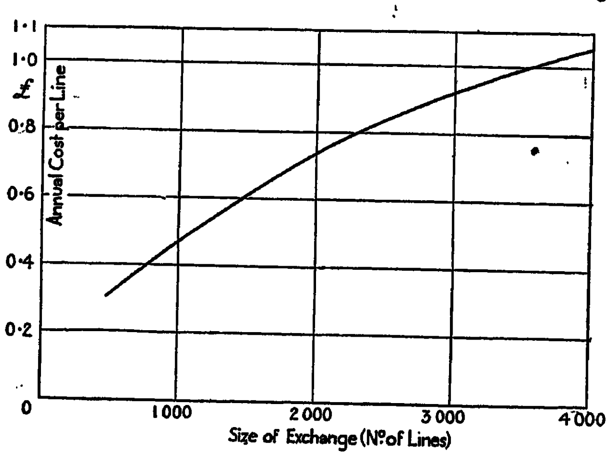

FIG. 9.—Subscribers' line costs for density = 1 500.

in the centre, the best position for which is generally more or less obvious, and this may be surrounded by one or more rings of small exchanges. The most economical position of the central and adjacent exchanges is then determined by inspection and a comparison of the costs of two or three alternatives.

Although the process is necessarily laborious, involving a large mass of calculations, an engineer experienced in this class of work can, within a reasonable time with the aid of these curves, work out the most economical layout for all but the largest towns.

In dealing with the larger towns, however, especially London, such a method would be unwieldy, and therefore the problem has to be attacked in a more indirect manner. It is assumed that the density, or number of subscribers per square mile, will be fairly uniform over the small portions of the area to be studied in separate

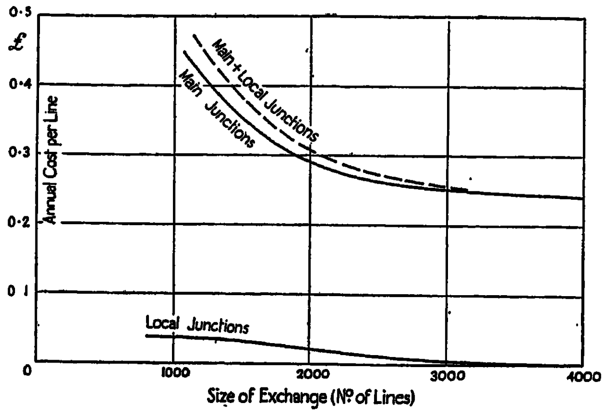

FIG. 10.—Junction costs for density = 1 500.

detail, which in the central part of the area is reasonably accurate. In order to relate the average length of a subscriber's line, and therefore the cost, to density and size of exchange, the graph shown in Fig. 7 has been prepared, based on Fig. 4 and the average cable costs.

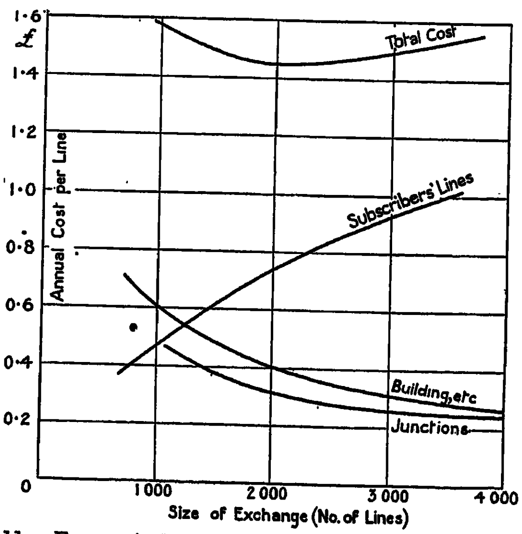

FIG. 11.—Economical sizes of exchanges for density = 1 500.

It will be noticed that the base of the graph is the radius of an equivalent circular area, not the size of exchange as in other graphs. This is found convenient for purposes of calculation because it combines the two independent variables, size of exchange and density. Numerically, the density is the number of subscribers per square mile.

In practice, of course, the exchange area is never

circular but, provided it is not very irregular and the exchange is properly placed at the telephone centre (that point which makes the total mileage of wire a minimum), the assumption introduces no serious error.

By means of this curve and the curves for junction and building costs already referred to, the economical size of exchange to serve an area of uniform density is arrived at, and a further curve (Fig. 8) can then be prepared giving the economical size of exchange for each density. Having this curve and the map showing the densities, the areas and location of the exchanges can then be set out, corrections being made for non-uniformity of density and other special conditions.

The application of the method may be illustrated by taking a typical area having a density of 1 500 subscribers per square mile. Fig. 9 shows the costs of subscribers' lines varying with the size of exchange, obtained from the curves already prepared. Fig. 10 shows similarly the cost of junction lines. The curve of total costs, Fig. 11, shows that for a density of 1 500 the economical size of exchange is about 2 000 lines.

It will no doubt be appreciated that this process represents only the first step in a case where an automatic system has to be grafted into an existing manual system. Allowance must be made for such factors as the layout of existing plant and the necessity for replacing each portion of the manual system only when it is economical to do so. This involves many considerations which it is unnecessary to detail here, but which all add to the complication of the problem confronting the engineer responsible for the layout of an exchange area and the economical introduction of the automatic system.

(5) Calculation and Layout of Internal Plant and Wiring.

After the position and capacity of a required automatic exchange have been settled, and a particular system has been chosen for adoption, there still remain many intricate problems to be studied and solved before the details of exchange design and specification can be matured. Subscribers' lines have only a small amount of apparatus allotted to the individual service of each. The great bulk of the exchange switching equipment consists of apparatus provided for the common use of all subscribers; its quantity depends upon the volume of traffic to be carried, and not upon the number of lines. There are many alternative ways in which the enormous number of selectable outlets involved may be grouped, and very careful calculation and planning are needed in order to arrive at the best economic layout and to ensure that the amount of switching plant at all points in the system shall be adequate to the requirements of the traffic without wasteful over-provision anywhere. It is necessary to prepare data of anticipated traffic for all classes of calls, and the average probable duration of the calls, known as the "holding time," has also to be determined. The amount of switching plant which will be simultaneously held in occupation during the busiest hour of the day depends on the product of "busy hour calls" and "holding time." This is expressed in what is known as "traffic units"—a term now standardized by the British Engineering Standards Association—in which holding time is reckoned in hours. Thus if each subscriber in a group of 100 makes, on the average, two calls during the busy hour, with an average duration of 3 minutes, the traffic originated will be $(100 \times 2 \times 3)/60 = 10$ traffic units. In other words, a traffic unit represents the equivalent of one hour's occupation of a switching channel. In most cases the switches engaged in providing a connection are engaged during its whole duration, and the calculated holding time for those switches includes the time to set up and to clear the connection, in addition to the period of conversation. Several recent systems involve the use of auxiliary sets of switches which are temporarily employed as steering switches to control the setting up of a through connection, and are then released. The holding time in the case of these switches averages only a few seconds, and a small number of sets can therefore handle a great many calls.

Another essential factor entering into the determination of the best economic layout is that known as "grade of service." Telephone traffic varies widely at different times of the day, and even the traffic of the "busy hour" shows considerable fluctuation from minute to minute. The provision of telephone plant in general is subject to the unfortunate economic condition that, so far as the bulk of it is concerned, its periods of idleness must greatly exceed its periods of employment. An endeavour to furnish an automatic exchange with switching facilities sufficient to ensure that exchange channels will be available for all calls at the peak of the busy-hour load in the busy season, would involve hopelessly uneconomic provision of expensive mechanism and would increase the cost of the service out of all proportion to the increase in its quality.

It is therefore necessary to fix a limit for the number of calls which may fail to get through on account of insufficiency of switching plant. This number must be so small that, to the subscriber, it is inappreciable. The proportion of calls that may be allowed to fail in this way in the busy hour represents the "grade of service" or "standard of service," and the Post Office has standardized a proportion of lost calls of 1 in 500 for each switching, with the proviso that if the traffic should increase temporarily by 10 per cent the grade of service shall not fall below 1 in 100. There are also certain modifications to cover special circumstances. Experience and observation have shown that the actual availability of switches, in groups carrying a given amount of traffic per hour, is closely in accord with the results obtained from a mathematical calculation of the probabilities, and, as is well known, the theory of probabilities is used, as far as it can usefully be applied, in the determination of the numbers of switches required.

For example, if a group of subscribers originating a given amount of traffic can be given access to a group of selectors, in such a way that each subscriber can reach any of the selectors, the application of the theory in order to determine the resulting standard of service is trustworthy and comparatively simple.

Most of the problems encountered in large areas are, however, too complicated to be readily solved by theoretical means. In the case quoted above each

subscriber will, in practice, obtain access to the first rank of selectors by means of a pre-selector or line switch having a limited number of outlets, say, 24. The number of first selectors required in the exchange may, however, be 1 000 or more, and the problem will be to arrange the inter-trunking of line switches and selectors in such a way that, while each line can only reach 24 selectors, the traffic of the exchange will be carried, at the specified standard of service, by a minimum total number of selectors. According to early automatic trunking practice the selectors would have been divided into independent groups of 24 and each group would have been multipled to as many line first selectors. The grading has 16 groups, each group comprising 75 subscribers with access to 24 outlets. There is thus a total of 384 outlets to be graded down to 128 selectors, and the way in which this may be done is shown in the figure.

It will be seen that each group of 75 lines has individual access to 4 selectors via exchange trunks, that it shares 4 further selectors with one other group, 3 with 3 other groups, and 7 with 7 other groups, while the remaining 6 selectors are at the common service of all the 16 groups, into which the 1 200 subscribers have been divided.

Each 75 lines has therefore access, complete or partial,

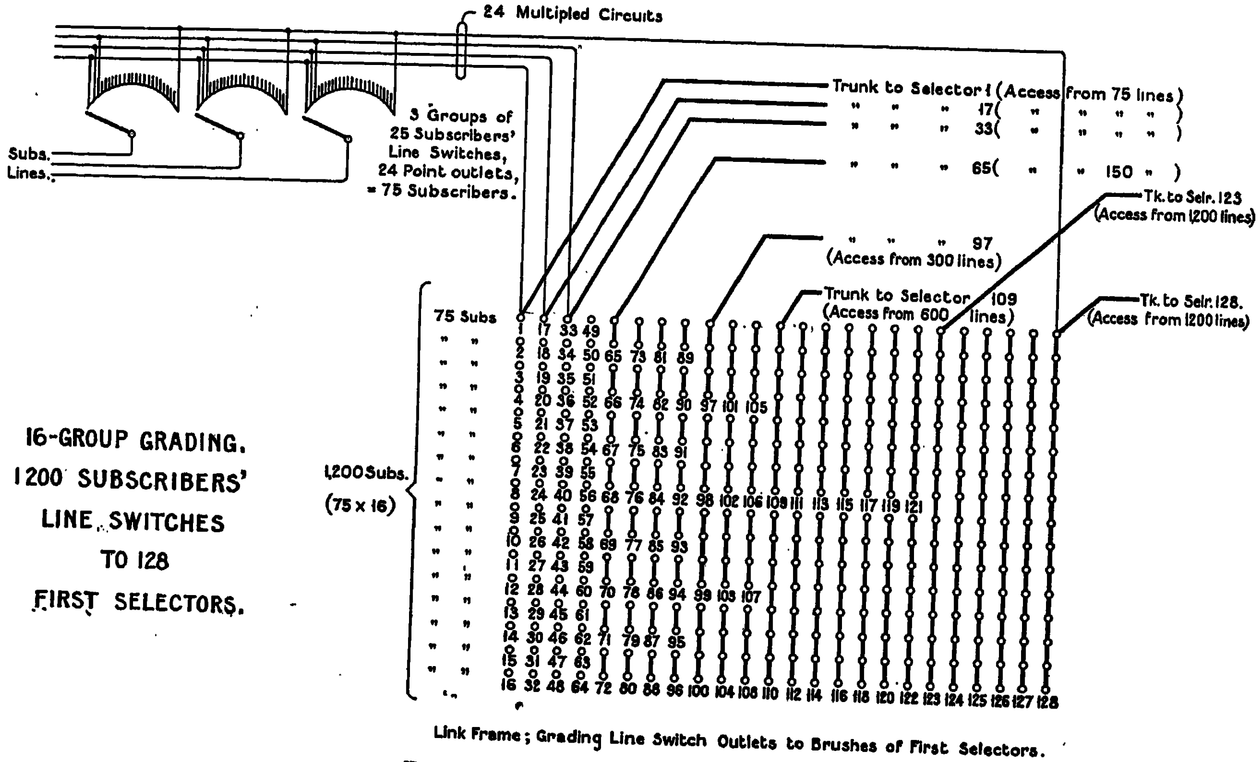

FIG. 12.—Diagram of group grading.

switches as it would suffice to serve during the busy hour. It has been found, however, that the average availability of selectors may be much increased by dealing with them in much larger groups, and by "grading" the multipled connections on the line switches in such a way that the 24 selectors to which each of them has access will be distributed throughout the larger group.

Fig. 12 illustrates the principle of grading applied to a group of 1 200 subscribers who require 128 first selectors to carry their originated traffic. Each subscriber is connected to a line switch having 24 outlets, and the outlets of 25 line switches are multipled together and terminated on a connecting rack. Any multiple of 25 subscribers may therefore be given access to one or more "individual" selectors, i.e. selectors to which that multiple, and no other, has access. In the figure, 1 200 subscribers' line switches are connected to 128 to 24 selector trunks, although its aggregate access necessarily remains equivalent to 8 trunks as below:—

Complete access to	4 trunks	= 4
Half access to	4 trunks	= 2
One-fourth access to	3 trunks	= 0·75
One-eighth access to	7 trunks	= 0·875
One-sixteenth access to	6 trunks	= 0·375
Mixed access to	24; aggregate access to	8

It should be mentioned that, as the selector trunks which represent the first choice of the line switches are naturally kept more fully occupied than those later in the series, and as the selectors themselves are arranged in groups of 10 having a common multiple, it is necessary to calculate the probable traffic in each and to connect them to the grading tags in such an order that each group of 10 will carry the same amount of traffic.

Apart from any method of grading, the best arrangement of the plant—in this ratio of 1 200 subscribers to 128 selectors, which is equal to 8 selectors for 75 lines—would have been obtained by combining the 24 outlets of 225 subscribers' line switches in a common multiple with access to 24 selector trunks. Assuming normal busy-hour traffic, this would have provided a standard of service of 1 lost call in 100.

Grading in 16 groups, as shown, raises the standard of service to 1 in 500 without involving the use of any additional plant. In the absence of grading, this standard could only have been attained by reducing the number of subscribers' lines served by 24 trunks and selectors from 225 to about 190—equal to an increase of 15 per cent in the required number of trunks and selectors. The economy effected by grading is therefore an important one.

Another, and older, method of increasing the traffic capacity of first selectors is to provide access to them via an intermediate set of secondary line switches or "preselectors." Many descriptions of this method have appeared in automatic literature, and it is not necessary to describe it here. There is good reason for believing, however, that, considering switching plant as a whole, the grading scheme effects substantially the same economy as the use of secondary line switches, while it has the great advantage of avoiding the circuit complications and the increased fault liability that the latter entails.

Problems similar to those mentioned arise in connection with the operation of hunting for disengaged trunking circuits between one rank of selectors and another. In this case the economic importance of securing optimum trunking arrangements is greatly increased by the fact that the next rank of selectors may be located in another exchange and the circuits may have to traverse some miles of street cables.

The increased traffic efficiency attending the selection of circuits in large groups has led to the design of selector switches which are capable of searching, or hunting, through much larger banks of trunking circuit contacts than the banks of 10 which are usually associated with the "step-by-step" automatic system. The rotary system of the Western Electric Co. searches over a bank of 22 circuits, while the panel system of the same company is arranged to search a maximum of 90 circuits and could probably, if desired, be arranged to search nearly 500 circuits. The switches of Messrs. Ericsson's machine-driven automatic system could also, if necessary, be arranged to find a disengaged circuit in a group of approximately 500. The direct step-by-step system is somewhat handicapped in this respect by the fact that the whole operation of searching for and finding a disengaged trunking circuit has necessarily to take place in the short interval between two successive pulls of the automatic signalling dial on the subscriber's telephone. In the case of machine-driven systems, such as those of the Western Electric Co. and Messrs. Ericsson, where the trains of signalling impulses are received from the subscriber by means of quick-acting "registers" which subsequently steer the call through the connecting switches, there is no such arbitrary time element to contend with.

It has, however, been possible to devise step-by-step switches which can search directly over a bank of 20 trunking contacts, two at a time, without exceeding the small time interval available. It is also quite practicable, on this system, to install suites of 10-contact or 25-contact "pre-selectors" between the various ranks of switches, and thus raise the theoretical trunk-hunting capacity to 100 circuits or 250 circuits. Such pre-selectors installed, say, between second selectors and outgoing junction circuits, would have their brushes joined to the selector banks and their multiple banks connected to the junctions. The selector can only find an outlet to the junctions via a pre-selector, the brushes of which are already standing on an idle line. Thus the actual searching movement is confined to the selector itself, and the time required for the operation is not increased by the introduction of the intermediate pre-selectors. Exhaustive study has shown, however, that by utilizing the methods of graded grouping already referred to, the need for large banks of trunk-hunting contacts, or their equivalent, can to a great extent be obviated, and that a satisfactory amount of traffic per switch can generally be carried even with 10 contacts in the bank level. It appears possible that the savings so effected in switch construction, and by the omission of the intermediate pre-selectors, will in most cases balance the cost of the proportion of additional junction circuits required for the 10-contact system, and selectors having banks of 10 contacts will therefore be used for ordinary services in the exchanges installed in London and throughout this country, unless and until further detailed study of local conditions indicates that facilities for increased searching range will at some points be economical.

It has been mentioned that the theoretical method of attacking problems of switching layout is often exceedingly difficult and leads to results which are tedious to evaluate. The most obvious alternative is to solve such problems by actual observations on working exchanges. There are two objections to this: first that it is difficult to control such tests—i.e. it is necessary to work with the traffic actually experienced, whether this traffic is that required to give salient points on traffic curves or not—and secondly, that the available range of "grade of service" is very small, so that it is not possible to find what deterioration is effected in the service by a given increase of traffic or reduction in the number of switches. For these reasons it has been a practice of the Engineering Department to make use of "artificial traffic" for the production of designing curves, and the results obtained are checked by theoretical calculation and by observations at working exchanges, where possible.

Two methods of producing artificial traffic have been used, one employing numbered counters and the other making use of the numbers in a telephone directory. In the first method 100 counters, numbered "01" to "99," are placed in a bag and shaken. Counters are then drawn one by one at random, each counter being replaced after drawing. The number of such drawings is made equal to the number of "busy hour" calls required for the test, and the number drawn represents for that call the interval of 1/100th of an hour at which

the call originates. By repeating the process and tabulating the results together, the time at which each supposed call originates may be determined to 1/10 000th of an hour. The times of the calls are arranged in sequence and are then available for the analysis of the effect of any desired grouping of switches. The holding time may be constant or variable, as desired. In the telephone directory method, the time at which a call originates (to 1/10 000th of an hour) is obtained by choosing a succession of 4 digits from the numbers in the directory. In general, tens digits only are used, as with the others there would be a tendency for certain digits to occur more often than others.

Each of these methods is, of course, merely an attempt to obtain a sequence of events in time according to the laws of pure chance, and so to represent the entirely fortuitous intervals at which individual calls are made during a short period when the aggregate amount of traffic is fairly constant.

As an illustration of the way in which the fluctuations of traffic are proportionately reduced as the size of a group increases, it may be of interest to consider the case of a number of subscribers each making two calls per busy hour with a holding time of 3 minutes. If these are arranged in a group of 10 having a common outlet, the resulting traffic would be equivalent to 1 traffic unit, and if the calls were made at absolutely uniform intervals they would all be carried by a single switching channel, continuously occupied. Similarly, a group of 250 lines would originate 25 traffic units and require 25 switching channels under the same conditions.

Actually, if this provision were made the following percentages of calls would be lost:—

	Per cent
For 10 lines (1 traffic unit and 1 switch) the loss would be	50
For 100 lines (10 traffic units and 10 switches) the loss would be	21·5
For 250 lines (25 traffic units and 25 switches) the loss would be	15
For 1 000 lines (100 traffic units and 100 switches) the loss would be	7·6

The matter may be looked at in another way as follows:—Assuming that the standard grade of service of 1 in 500 is given, it is found that the average traffic per switch for the numbers of switches quoted above and in two graded cases would be as follows:—

10 Switches will be asked to carry 3·43 traffic units per hour; average traffic units per switch	0·343
25 Switches will be asked to carry 13·76 traffic units per hour; average traffic units per switch	0·55
100 Switches will be asked to carry 76·4 traffic units per hour; average traffic units per switch	0·764
100 Switches (10-contact grading), 43·6 traffic units per hour; average traffic units per switch	0·436
100 Switches (25-contact grading), 64·08 traffic units per hour; average traffic units per switch	0·641

In the first three cases the pre-selectors finding their outlets via these switches are assumed to have a sufficient number of contacts to secure full availability; in the two last (graded) cases the pre-selectors would have only 10 and 25 contacts respectively.

(6) SERVICES RESERVED FOR MANUAL OPERATION.

The conversion of an area to automatic working does not involve the complete elimination of the manual operator. Some classes of traffic can at present be handled more conveniently and economically by manual than by automatic means and, in general practice, all calls for which more than the unit fee is charged will be dealt with by an operator who will record each call on a ticket in order that the proper debit may be made to the calling subscriber. In the Post Office system, operators are retained for trunk and toll circuit calls, extra-fee junction calls, phonogram (i.e. telegraph message) calls, call-office and coin-box station calls, and for "inquiry" and "information" calls.

Until recently all coin-box and call-office traffic was handled manually, but a new form of coin-collecting box has now been introduced which provides for the deposit of the local unit fee automatically. The attention of an operator will only be required for calls involving the deposit of additional coins in the box. The use of this new coin box in association with automatic systems will, in the first instance, be confined to provincial areas.

For all calls to points outside the unit-fee area, the originating automatic subscriber dials a number which will obtain the attention of an operator in his own local exchange, or in the trunk or toll exchange, to whom he gives his demand. The call is than handled and recorded on a ticket in the regular manual fashion throughout.

The method known as "dialling out," which permits the calling subscriber to obtain direct communication with an operator at the distant exchange required, is frequently advocated, but has not been adopted by the Post Office for extra-fee traffic, on account of the disadvantage of removing the supervision of such calls from the operator at the home exchange. The distant operator cannot conveniently be placed in a position to check the identity of the calling subscriber against whom the extra charge is to be debited.

The converse procedure of "dialling in" is, however, in common use. A subscriber on a manual exchange who requires a subscriber on an automatic exchange, reached by means of a junction or direct trunk line, makes the demand to his local operator as usual. This operator then completes the call by dialling from her cord circuit over the junction or trunk line directly into the switches at the automatic exchange, and thus sets up the desired connection without the intervention of an operator at the called exchange. This method of operating is adopted in all cases where line conditions permit, in preference to the alternative method of passing the demand verbally by order wire, or over a signalling junction to a manual operator at the required automatic exchange for completion.

The character of the line has, however, a restrictive effect upon the extent to which "dialling-in" can be em-

ployed. The method is practicable on almost any length of unloaded physical line, but the introduction of loading coils and repeaters and the use of phantom circuits give rise to certain difficulties. The transmission constants of a loaded line introduce a marked degree of distortion in the dialled impulses, but in the few cases where this trouble would be sufficient to affect working efficiency it would be possible to remove the difficulty by the use of special methods and apparatus.

Repeaters and phantom circuits are, however, obstacles which have not yet been fully overcome. A solution has been found to the cognate problem of sending calling and supervisory signals over such circuits, and considerable progress has been made with the solution of the dialling problem. A method which promises a satisfactory result involves the use of high-frequency alternating currents, the application of which to the line at the sending end is controlled by the dial impulses. At the receiving end these trains of high-frequency alternations operate on the grid of a valve having in its plate circuit a relay which, in turn, controls the stepping relay of the selector switch.

In ordinary local areas of medium size an endeavour is always made to change over from manual to automatic working simultaneously at all the exchanges in the area, but this is often impracticable and in such cases one or more exchanges remain manual whilst the remainder are automatic. Under such conditions the methods of "dialling-in" and "dialling-out" are both adopted for interchange of traffic between the two systems, and each call is dealt with by one operator only.

There is no objection to allowing an automatic subscriber to dial out to the operator at a manual exchange in the case of unit-fee traffic, since the registration of the call is automatic and the operator, who has no extra charges to record, is not concerned with the identity of the calling subscriber.

(7) The Problem of very Large Areas.

Although it has long been recognized that the mechanical switching possibilities of automatic selecting apparatus are theoretically unlimited, there have been difficulties of a very practical kind in applying it to the telephone service of the largest area systems which have grown up in manual exchange practice. Up to a few years ago it was necessary to envisage an automatic intercommunicating area as laid out upon a perfectly uniform and rigid scheme of exchange numbers for the subscribers in all parts of it. The first digit of each number had to choose a line to a particular district, every subscriber in which must have a number commencing with that digit. There might be another digit to choose a particular exchange in the selected district, in which case all the subscribers' numbers on that exchange would have to commence with the same two digits. A further four digits would suffice to choose any subscriber's line in an exchange of 10 000 lines, or in a group of smaller exchanges of 10 000 lines' aggregate capacity. Such a system would be a straight 6-digit system or its equivalent and, as one or two initial digits have to be reserved for special purposes, it would serve a maximum of about 700 000 subscribers' lines. If it were possible to construct the whole system *en bloc* and to transfer to it all existing subscribers on a given day, on which day a brand-new telephone directory would be brought into use, the fact that every number on the system had been changed might not present too serious a difficulty. In reality, of course, the process of transfer must generally extend over several years. The economic advantage of the automatic system is not usually sufficient to justify the scrapping of adequate and up-to-date manual exchanges, and there is generally a long interim period during which the two systems must exist side by side. So long as a rigid numbering scheme was essential the successive transfers of groups of subscribers, as additional automatic exchanges were opened, occasioned in each case a certain amount of dislocation of the service. The continual change of indefinite groups of numbers in the directory, and the consequent alterations in the methods of initiating and handling the traffic concerned, were exceedingly troublesome to subscribers and operators alike. Another condition necessarily attending the layout of an area under a rigid numbering scheme is that in all parts of it a definite allocation of spare numbers must be made at the outset, in order to provide for future development at each particular point during a period of many years. Similarly the layout of main switching centres, the number, capacity, and approximate positions of all exchanges, the routing of traffic between them, and the capacity of the routes followed by external junction lines, must be settled long in advance of the maturing of full requirements. Telephone development is affected by so many uncertain factors—commercial, social and political—that it is very doubtful whether even the most careful forecasts of ultimate development could be relied upon to avoid the probability of enormous expense and inconvenience in providing for errors and in correcting them. A further possibility of danger arose from the fact that the handling at manual exchanges of calls for automatic subscribers absorbed more of the operators' time than ordinary calls. As the proportion of such transfer calls increased, the traffic capacity of each manual exchange would be correspondingly reduced and additional operators' positions, with in some cases extensions of buildings, would be necessary to serve the existing manual subscribers at unconverted exchanges. There would be many cases in which such extensions could not be made and a very critical position might arise. So serious did these aspects of the matter appear that telephone engineers responsible for providing the means of carrying on uninterrupted service in the large and immensely important areas represented by New York, London, and other great cities, hesitated to embark upon the task of introducing the automatic system in these areas.

As already mentioned, the preliminary installation of a semi-automatic system throughout the area, followed by a final quick change-over to full automatic, presented a solution—although an uneconomical one—of some of the difficulties of the transition period, but it did not provide any way out of those affecting the subsequent development of the area on the basis of a rigid numbering scheme.

A notable attempt to solve the London automatic

problem was described in a paper * by Messrs. Laidlaw and Grinsted, read before this Institution in 1919. The authors proposed to divide London into nine regions, each expected to serve about 100 000 subscribers, and to mark the names of these nine regions on the subscribers' calling dials, adjacent to digits 1 to 9. The main switching exchange in each region would bear the regional name, and would be reached, by the first pull of the dial, from any subscriber's station in London. Access would be obtained through it to all the other exchanges in the region. Subscribers' numbers would all be changed and would consist of the regional name followed by 5 digits, or possibly by 6 digits. In a 5-digit system, for example, "Wimbledon 1829" might become "South 71829," the digit 7 being used to steer the call into the Wimbledon exchange. ("Wimbledon 19" would become "South 70019.") The initial digit "0" would be used to gain the attention of an operator for all service purposes and for the completion of all calls to points not included in the nine London regions. The proposal was very ably worked out, but it was felt by the Post Office that it failed to provide the traffic and engineering conditions necessary for the satisfactory introduction of automatic working in the London area. It postulated a rigid numbering scheme, with eventual alteration of all existing subscribers' numbers; an inflexible routing scheme which involved, *inter alia*, the provision of direct junction circuits from every main exchange to all the regional centres. Only 10 exchanges in each region of 100 000 lines could be selected by means of the second digit, but the most economical layout of the regions would seldom be secured by 10 exchanges of 10 000 lines each. In some cases the number would approach 20 exchanges of correspondingly reduced capacity. An exchange of 4 000 lines, for example, would therefore have to be reached, through a nominal 10 000-lines' centre, by 4 separate third digits, each representing the selection of a group of 1 000 lines. Junction circuits would have to be provided for each group independently, instead of as a common stock available for the full 4 000 lines. Such conditions tend to involve excessive provision of external plant. The scheme also dictated a certain artificial sequence of exchange transfers—inasmuch as in every case the main regional exchange would have to be made automatic before any other exchange in the region could be dealt with—which would have been liable to involve heavy economic wastage. Some of the interim arrangements proposed for the transition period would also have led to troublesome repercussions in practice. (These remarks are, I think, quite consistent with high appreciation of the value of the contribution made by Messrs. Laidlaw and Grinsted to the general study of the subject.)

(8) The "Panel" System of the American Bell Companies.

Such was the London position until in 1919 we began to hear rumours that the long-continued and quite unadvertised efforts of the American Telephone and Telegraph Co. and its associated manufacturing concern, the Western Electric Co., had succeeded in evolving a system which obviated all the well-known difficulties, and that it had actually been decided to commence its installation in New York. The basis and general arrangement of the new system—the "panel" system—had been known in this country for some time, but details of its most recent development were lacking until Mr. McQuarrie of the Western Electric Co. visited this country early in the year. Mr. McQuarrie's description of the new operating features which had been grafted on to the system came to me as a veritable flash of light. It was at once evident that, by the invention and application of the digit translators, numerical call indicators, etc., which he described, most of the old bogies had been disposed of, and that a way had been opened for the direct application of the automatic system to telephone areas of the very largest size. Initial preparation could be made at all exchanges in the area without affecting the service, and thereafter the installation of automatic plant could begin at any

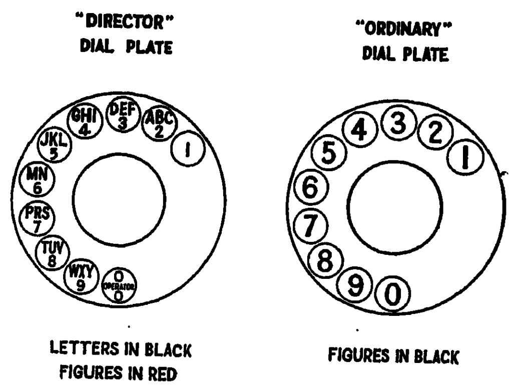

Fig. 13.—Automatic dial plates.

points where new exchanges were required. The routing of calls through various switching centres could be arranged in accordance with the actual needs of the traffic and could be modified from time to time as development might dictate. There was no need for any wholesale change of exchange names or of ordinary subscribers' numbers; all that was necessary was to alter a few names which were alphabetically or numerically similar to others, and to level 2-digit and 3-digit subscribers' numbers up to four digits. (Even these comparatively trivial modifications are quite sufficiently troublesome in practice.) The arrangements for interchanging calls between automatic and manual exchanges permitted of rapid operating and tended to raise, rather than to lower, the traffic capacity of existing manual exchanges. Each subscriber, automatic or manual, could make all his calls in a uniform manner and would not require to distinguish in any way between calls for correspondents served by automatic or by manual exchanges. Above all, a directory which would give no trouble to any subscriber could be prepared once for all, in advance of the first exchange transfer, and could be maintained unaltered throughout the whole transition period and into the subsequent full automatic

* "The Telephone Service of Large Cities," *Journal I.E.E.*, 1919, Supp. to vol. 57, p. 158.

period, apart, of course, from ordinary additions and deletions.

The subscribers' calling dial with a combination of letters and numbers, first introduced in connection with the panel system, has frequently been described and is becoming fairly well known, and the same applies to the arrangement of the directory pages.

Fig. 13 shows the finger plate of this dial, as well as one of the ordinary type. The subscriber is required to dial the three initial letters of the required exchange, followed by the four digits of the called subscriber's number. The three letters which appear in each of the finger holes of the dial have, of course, the same numerical significance, and produce the same effect upon the switching mechanism as the digits which occupy the same positions; the use of letters is purely a matter of convenience. The three initial letters of each exchange must represent a different combination of digits from those of any other exchange. Obviously, therefore, the two names "HAMmersmith" and "HAMpstead" must not exist together in the same area, and the same would apply to two such names as "Victoria" and "Thames" since the pulls of the dials

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Argentina Brazil & Chile Shipping Co
70 Wall.HAN over 0307
Argentine Genl Consulate. 17 Batry pl..REC tor 6946
Argentine Impt & Expt Corp. Prod Ex...BRO ad 1768
Argentine Mercantile Corp. 42 Bway... .BRO ad 5066
Argentine Naval Commission. 2 W 67..COL mbus 5623
Argentine Quebracho Co. 80 Maiden la.....JOH n 1652
Argentine Railway Co. 25 Broad.......BRO ad 1383
Argentine Trading Co. 1164 Bway......MAD Sq 1871
Argeres Bros. Restrnt. 86 6th av......SPR ing 5337
Argero A. Grocer. 119 9th av........CHE lsea 6255
Arghis A. Tobacco. 74 Wall.........HAN over 6311
Argirople Theodore. Jwlr. 406 8th av..FAR ragut 9772
Argo Packing Corpn. 705 Greenwich...FAR ragut 4505
Argon Dress Co. 24 E 12..........STU yvsnt 2011
Argonaut Supply Corp. 50 Union sq..STU yvsnt 7476
Argonne Steamship Co. 17 Battery pl...REC tor 2493
Argos Ad-Art Co. 1133 Bway........FAR ragut 5986
Argosy The (A Pub). 280 Bway.......WOR th 8800

FIG. 14.—Extract from a New York telephone directory.

represented by VIC are identical with those of THA. Fig. 14 shows the arrangement of part of a directory page. The block printing of the first three digits of the exchange names does not at all inconvenience the manual subscriber who passes his calls verbally, and it indicates to the automatic subscriber that these three letters must be dialled in order to reach the exchange in question.

As already indicated, the panel system is so equipped that each subscriber obtains communication with all his correspondents, manual or automatic, in the same manner, and is therefore quite unaffected by the successive conversions of exchanges, other than his own, from one system to the other. So long as his own station remains manual he passes all calls to his exchange operator verbally as usual and, as soon as his own exchange has been converted to the automatic system, he uses his calling dial in exactly the same way for calls to either type of exchange.

This result is achieved by the introduction of "call indicator" equipment of types substantially similar in operating principle to those which have been adopted for the London automatic system, as described later (see Figs. 22 and 23).

A detailed description of the panel switching system and its modes of operation—which represent a remarkable aggregate of invention and design—would occupy several volumes, and only a brief reference to it can be made here. Its evolution was only undertaken after a thoroughly comprehensive study of all existing automatic systems, and with the specific object of producing a system specially adapted to service in the largest and most densely telephoned areas, which would be capable of furnishing every kind of service that the manual system, with its operators, has ever been called upon to supply. A preliminary description, by Gherardi and Charlesworth, was printed by the Associated Bell Companies in 1920, and a fuller general description was presented in a paper* by Craft, Morehouse and Charlesworth, read at a convention of the American Institute of Electrical Engineers in 1923.

The installation of the system has been rapidly pushed forward and it has now been equipped in New York and some other large American cities to a capacity of more than 250 000 subscribers' lines.

The system derives its name from the design of the selector switches, the multiple contact banks of which are arranged in large flat panels over which the contact brushes move in vertical lines. Its moving parts are all machine-driven by means of a system of rotating shafts maintained in continuous motion by specially designed motors of practically unvarying speed. Its electrical design differs profoundly from that of step-by-step systems with straightforward selection by decimal stages. In general the movements of the switches are governed by what is known as "revertive control," that is to say they are not actuated by impulses sent into them but, after having been started, the switches themselves send impulses back into the controlling mechanism, which counts the impulses and stops the movement of the switches when the required position has been reached.

The number of circuit outlets among which a panel switch can exercise selection is not limited, as in the step-by-step system, to 100, but has, in fact, been made 500; that is to say the successive selections do not follow in decimal sequence.

Since the subscriber's calling dial transmits a series of plain decimal impulses, it is necessary to provide means for receiving these impulses and translating them to a non-decimal basis before they are used for controlling the movements of the switches. This function is performed by a combination of apparatus—called a "sender"—situated in the exchange of the calling subscriber. In the sender the decimal impulses sent out from the dial are accepted, stored, translated and finally sent out, in any desired sequence of impulse trains, to route the call through any necessary intermediate switching centres to the required exchange, and, finally, to reach the line of the called subscriber. Complete numbering and trunking flexibility is thus provided.

As already mentioned, the motion of the selector

* *Journal of the American Institute of Electrical Engineers*, 1923, vol. 42, p. 320.

used in the panel system is vertical only; when hunting for a circuit it moves upwards, and when released it returns downwards to its normal position of rest. The movable portion of each selector consists of a long tubular metal rod carrying six triple-contact brushes. One of these brushes fixed at the top of the rod moves over a flat commutator in combination with which it controls the extent of the motion and also extends the three wires of the selector circuit to the other five brushes. These five brushes are spaced equidistantly on the tube and have in front of them the flat panel multiple of 500 circuits. Each brush has access to 100 of the circuits and each selector can therefore make connection with any one of 500 circuits. Motion either upwards or downwards is imparted to the rod and brushes through the medium of magnetic friction clutches placed at the bottom of the rod in association with the constantly rotating power shafting.

The panel with its five sections of 100 lines each, placed one above the other, is fitted in the centre of an iron framework.

Each section is built up of flat punched strips of brass or other suitable metal about 42 in. long by 1 in. wide. There are three strips to each circuit, two of these corresponding to the line wires and one, used for local control purposes, corresponding to the sleeve connection of manual exchange circuits. The 300 strips in a panel are securely bolted together and are insulated from each other and from the framework. The two long edges of a strip are each formed with 30 projections with which the selector brushes can make contact. Selectors to the number of 60, with their vertical rods and brushes, are associated with each 500-line panel, 30 of them being mounted on the front and 30 on the back of the panel. Each of the 500 sets of three metal strips, with their front and rear projections, thus represents, in itself, a multipled line with which any of the 60 selectors can connect the circuit of its brushes.

When a selector is searching it is trying to find either a particular circuit or a disengaged circuit in a particular group. That circuit or group of circuits will appear on only one of the five 100-line sections of the panel, and it is necessary that, of the five brushes on the selector which are all connected together in multiple, only the one opposite that particular section should be active. Each brush is therefore normally retained in an inactive position, and it is arranged that in the process of selection, before searching begins, the correct brush shall be thrown into the active position. This is effected by means of a rod carrying trip fingers, one of which unlatches the selected brush as soon as the brush rod begins to move upwards. The four brushes opposite the other sections of the panel remain inactive and pass over the projecting contacts on the line strips without touching them.

Associated with each selector is a "sequence switch," the function of which is to make and unmake in the proper order the various circuit combinations required as a connection progresses through its various stages. This very important item consists of a central shaft fitted with a number of cams, or segmental contact rings, so cut that the various contact springs associated with them close and open circuits in a definite sequence and at definite points during the motion of the switch from position to position. The switch has 18 positions, in any one of which it may be stopped as required. It is operated by means of an electromagnetic clutch from the motor that drives the selectors.

Fig. 15 is a general view of a selector frame. The five panels are marked P, the commutators at the top are marked C, the brushes are marked B, and the brush-carrying tubes E. At the bottom the clutch magnets are marked M. The sequence switches and other apparatus associated with the selectors can be seen on the frame at the sides of the panels.

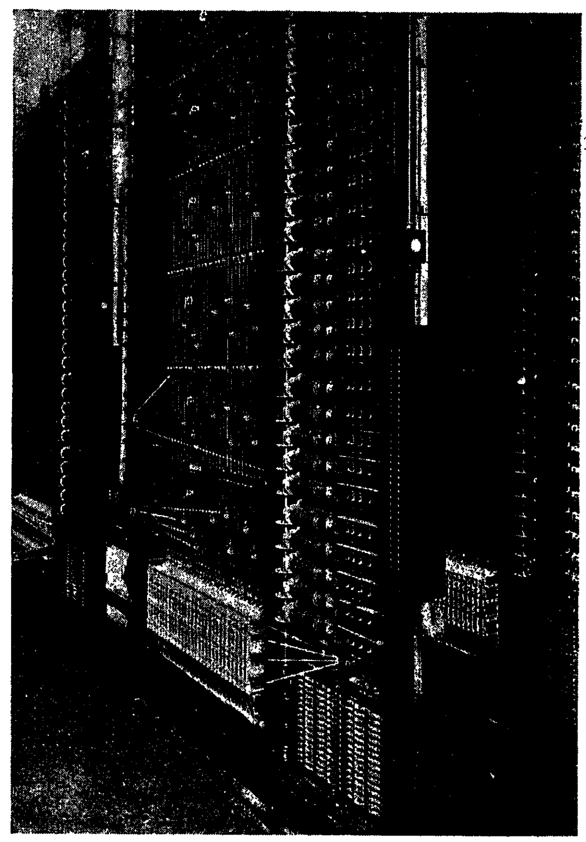

FIG. 15.—Panel selector frame.

Four principal types of selector besides a line-finder switch and a sender selector are used in the panel system. These four are all similarly constructed, but differ in circuit details. Their relative positions in making connections are shown in Fig. 16.

For calling purposes, subscribers are connected in groups of 300 to line-finder switches which are of the same construction as the selectors except that there are 15 panels of 20 lines each and 15 brushes per switch. When a subscriber lifts his receiver to make a call he operates a relay at the exchange, bringing a line-finder into use. The particular brush opposite the 20 group in which the subscriber's line is situated is tripped and hunts for his line. When the line is found the switch comes to rest with the brush on its terminals. At the

same time a sender selector, which may be a switch of the rotary type, hunts for a disengaged sender which it connects to the line-finder and to a district selector associated with the latter. The subscriber now hears a tone signal, and as this is an indication that he may do so, he dials, in order, the first three letters of the wanted exchange name and the four digits of the wanted subscriber's number. The dialled impulses having been received and translated in the sender, a circuit is established between the sender and the district selector. The object at this stage is to extend the calling subscriber's line by means of a junction to the exchange of the wanted subscriber. The district selector has access to a total of 500 circuits; but as 45 of these are used for local service purposes, the maximum number of outgoing circuits which it may use is limited to 455. As the total number of junctions outgoing from an exchange is likely to be very much greater, it is necessary to place the outgoing ends of most of the junctions upon office selectors and to arrange for the district selector to find either a junction direct or a circuit to an office selector having access to the desired junction group.

As soon as the fundamental circuit is established between the sender and the district selector, a clutch on the latter is operated and the brushes move upwards. After they have taken one, two, three, four or five steps the circuit is interrupted by the sender, and the brush trip magnet on the district selector operates, so that when the brushes again move upwards the one associated with the 100-line section of the panel containing the required junction group will be tripped into the active position. There may be several junction groups on this section, and therefore the next selective operation is to find the right group. The fundamental circuit is now re-established, the district selector again moves upwards and, as it does so, sends impulses back to the sender. The sender counts them and, when the number corresponding to the position of the group on the panel is reached, the sender again interrupts the fundamental circuit and the district selector comes to rest with the brush resting on the terminals of the first circuit in the group. If that circuit happens to be engaged, the district selector is re-started and

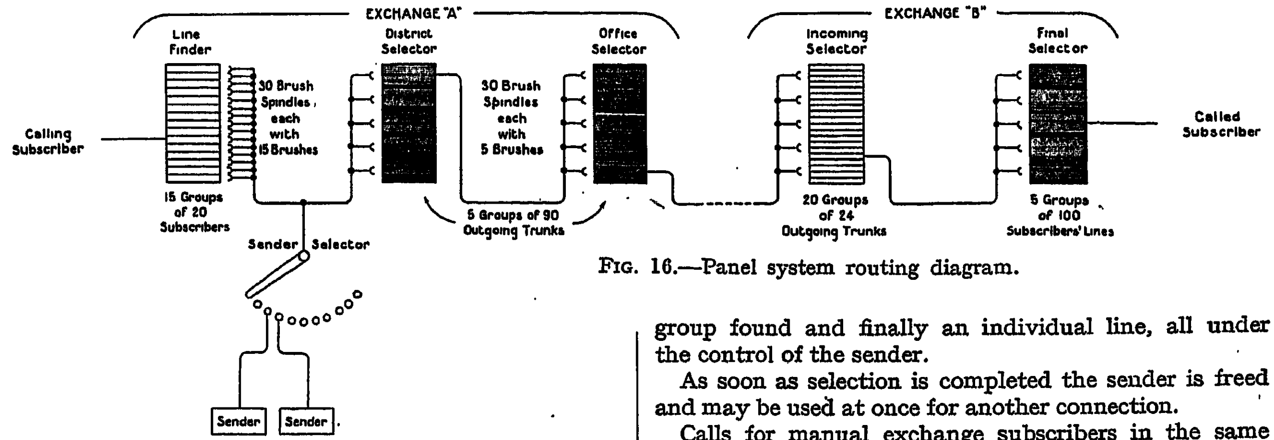

FIG. 16.—Panel system routing diagram.

continues upwards till it finds a disengaged circuit and makes connection to an office selector.

A similar sequence of operations having taken place at the office selector under the control of the sender, connection is made to an incoming selector at the wanted exchange.

Now, as the unit of the system is an exchange of 10 000 subscribers' lines—numbered from 0000 to 9999—and as 500 subscribers' lines are multipled on each final selector, there will be 20 groups of final selectors in a fully equipped exchange. It is arranged, therefore, that each incoming selector shall be equipped with a multiple of 20 groups of 24 circuits each, outgoing to final selectors, distributed four groups per panel. The process of selection at the incoming selector is again a matter of tripping a brush, finding a group, and finally a disengaged circuit to a final selector: this is done by the process used in the previous cases, under control of the sender.

At the final selector a brush has to be tripped, a tens group found and finally an individual line, all under the control of the sender.

As soon as selection is completed the sender is freed and may be used at once for another connection.

Calls for manual exchange subscribers in the same area, which are dialled in exactly the same manner as calls for automatic subscribers, are taken by the sender, translated and sent out to the manual exchanges, where they are displayed on call indicators in front of the junction operators as already mentioned.

It will have been gathered that the "sender" which controls all these operations is a remarkable piece of electrical equipment. In addition to the duties already mentioned, however, it fulfils a multiplicity of other functions. It has to distinguish the type of exchange to which a call is destined, so that it may control the operations associated with the progress of a call to an automatic exchange in one way, and to a manual exchange in another way. It distinguishes between calls for a terminal exchange and those for a tandem exchange, and causes them to be operated in an appropriate manner for each case. It distinguishes between connections which will pass out over loaded and unloaded lines, and it directs the selector switches in the setting up of the proper transmission conditions accordingly.

Certain senders associated with groups of coin-box lines test the calling lines and determine whether the callers have deposited the necessary coins before putting connections through. They also determine in each case

whether a fee is chargeable, and cause the coins deposited either to be collected or returned to the callers. When its work is done the sender must cut itself free and return to its normal condition in readiness for another transaction.

An idea of the electrical intricacy of a 7-digit sender may be gathered from the *skeleton* diagram shown in Fig. 17.* It must be recollected that only a small fraction of its total equipment and wiring is illustrated, and that such items as the multi-contact "sequence switches" are not shown as such, but appear merely as conventionally numbered contacts interpolated in the parts of the wiring scheme to which they apply. In order to read the diagram intelligibly, it would be necessary to have full information as to the time sequence in which these contacts are operated by the driving mechanism. It will be agreed that the sender is a formidable electrical item!

Fig. 18* shows the form of contact brush used on the panel selectors, and gives a view of the machine tools, assembling and adjusting tools, testing jigs, etc., required to manufacture it. The contrast between the tiny brush and the great array of necessary tools illustrates the high degree of machine-shop organization involved in modern quantity production.

The panel system in its entirety includes a multitude of electrical circuits of great complexity. It is the product of many wonderful brains, and its rapid development and installation are the outcome of probably the greatest engineering effort so far made in any field of industrial endeavour. Its future will be followed with keen interest by all telephone engineers.

(9) The Choice of a System for London.

Four years ago the development of the "panel" system had reached a stage which placed it far in advance of other then existing systems in respect of suitability for the equipment of the largest cities. The Post Office was eager to start the introduction of automatics in London, as many large new exchanges were required to provide for development and for the replacement of existing obsolescent or inadequate exchanges, and the installation of these important exchanges on the manual system would have had the effect of postponing by many years the ultimate complete conversion of the area to automatic working. The panel system was, therefore, very closely studied and the opinion reached was so favourable that it was decided to proceed as rapidly as possible with the preliminary arrangements for its adoption. It was admittedly both costly and complex; much design and engineering work still remained to be done before it could be said to have reached a state of comparative finality, and many of its features, which had been developed to meet the telephonic conditions of to-day in New York, could not without modification be applied to the very different conditions of London. On the other hand it was obviously a system of unbounded possibilities and no one doubted that it could be made to meet any legitimate service requirement that might arise. A factor not to be overlooked was that it had behind it the high prestige of the American Bell System, which had staked very large financial commitments on its success, and whose able engineers would, for years to come, continue to strain every effort to bring it to perfection.

* Not reproduced in the *Journal*.

Plans were prepared for a first panel exchange in London, to be known as "Blackfriars," and at the same time the Post Office started to negotiate an agreement with the Western Electric Co., in accordance with which the manufacture of panel equipment would have been commenced in England under conditions that would ultimately have permitted other British telephone manufacturers to obtain a share of the work. While these arrangements were proceeding, the sponsors of step-by-step automatic systems had not been idle or asleep, and early in 1922 the Automatic Telephone Manufacturing Co. called our attention to a notable development of the Strowger system by the Automatic Electric Co. of Chicago, who had succeeded in devising and combining with the step-by-step system a call-storing and translating scheme, which had endowed that system with practically the same elements of numbering and trunking flexibility that had first been conceived in association with the panel system. To this new development the name "Director System" was given. The matter was, naturally, one of first-class interest and, although the immediate proposals were in a somewhat embryonic stage, they were at once investigated very fully.

In association with the Automatic Telephone Manufacturing Co.'s engineers, a miniature multi-exchange system was laid out in such a way as to cover as far as possible all the different types of service required and exchange conditions met with in London, and was installed at the General Post Office as a working model of the director system. (A similar working model formed part of the Post Office exhibit at the British Empire Exhibition at Wembley.) Exhaustive study and trial led to the conclusion that the director system contained all the essentials required as a basis on which to frame a complete equipment of circuits and apparatus admirably fitted for the service of such an area as London, and it was evident that a practicable alternative to the adoption of the panel system had become available. In November 1922 I definitely recommended the adoption of the step-by-step system, with the addition of the "director." The main reasons on which that decision was based may be of interest, and are as follows :—

(1) The first cost of director exchanges was somewhat lower than the probable cost of the panel system manufactured in England.
(2) The fundamental electrical plan of the system is very much simpler than that of the panel. Circuits for particular purposes are easier to design and easier to understand.
(3) The Post Office engineering staff was already familiar with step-by-step systems, and it had been found that men could readily be trained to undertake all the duties of maintenance. The difficulties involved in securing and intensively training the requisite staff for handling the panel system—on the large scale of the

necessary programme—would certainly have been considerable, and might have involved serious delay.

(4) The apparatus to be employed in the director system was all of existing types which had stood the test of years of actual use, and which could be depended upon to give first-class service. The scheme was purely one of new electrical circuits and combinations. It was possible, even at that early stage, to visualize the lines on which circuits for all purposes might be designed and, in fact, to see right through the eventual London system to a far greater extent than was possible in the case of panel equipment.

(5) The director system applied readily and naturally to small, as well as to large, exchanges and to "satellite"* exchanges as well as main exchanges. The panel system had not been developed with a view to serving small or satellite exchanges. The fact that it could be made to do so was not doubted, but it did not appear that the solution was likely to be an economical one. This would be a matter of little importance in New York where the dense population of its large business buildings and apartment houses, combined with its high percentage of telephone development, necessitates that nearly all exchanges must have a capacity approaching 10 000 lines. In the "down-town" area of New York many of the exchange buildings will have capacity for four or more exchange units of 10 000 lines each. In widespread and less opulent London there have to be very many small exchanges and satellite exchanges, and it is essential to have a system which can be applied economically to such conditions. It is estimated that in 10 or 12 years' time there will be at least 130 separate exchanges in the London area. Of these not more than about 50 will be in the business districts of the City and West End, and of this number only about 30 will have an ultimate capacity of 10 000 lines, while about 20 will be limited to 5 000 lines. The remaining 80 exchanges in the area will include about 50 of 3 000 lines, 20 of 2 000 lines, and 10 of 1 000 lines. (In several cases two or three exchange units of 10 000 lines each will be accommodated in the same building.)

(6) The Post Office was already committed to several variations of the step-by-step system on a considerable scale in the provinces. The possibility of using the same system in London replaced the somewhat dismal prospect of adding another and very complex system to the rather divergent group already established, by the much more attractive prospect of being able to standardize a type of automatic system for general use throughout the country. As a direct result of the adoption of the director system, a large measure of standardization has since been accomplished, as referred to later. It will in future be possible to move staff from one district to another as may be necessary, without confronting the transferred men with unknown types of apparatus and circuits in the exchanges.

(7) Prior to the adoption of the director system, it had been ascertained that arrangements could be made for spreading the work among the regular exchange contractors of the Post Office at an early date. The important question of supply was thus greatly eased, as existing British factories became at once available for production purposes. The necessity for placing even the initial orders abroad was avoided, and the Post Office was able to enlist the co-operation of the skilled engineering staffs of all the contractors who had been producers of step-by-step equipment.

* A "satellite" exchange is one provided only with subscribers' line switches and local selectors, and dependent upon an adjacent main exchange for all manual services and for the routing and handling of all its external traffic.

The negotiations in hand for the introduction of the panel system were therefore broken off and agreements were entered into with the Automatic Telephone Manufacturing Co. for the supply of director switching equipment for the equivalent of about 55 000 exchange lines, and with the Western Electric Co., Messrs. Siemens Brothers and the General Electric Co. for smaller quantities. Provision is made for existing patents, and for future patents during a specified period, to be pooled on terms which will enable the Post Office to call upon all the firms to install plant covered by patents in the possession of any of them. At the end of the period of about three years covered by the contracts it will also be possible to utilize the services of other competent firms who may desire to take up the manufacture of step-by-step automatic equipment. These agreements cleared the way for standardization of system, and before proceeding to specify circuits and layout a very careful comparative study was made of the characteristics of the systems identified with each of the firms named, of all of which the Post Office had had practical experience.

Subsequent to the decision to adopt the director system, the firm of Siemens Brothers had submitted analogous developments styled the "translator" and the "by-path" systems, applicable to its type of step-by-step equipment, and at a later stage the General Electric Co. also brought forward a proposal to embody in its system an equipment of devices having the same object, which had been termed the "controller" system. The "translator" and the "controller" systems existed, for the most part, on paper, but they furnished interesting evidence of the readiness and flexibility with which the long-established step-by-step system lent itself to the grafting on of developments designed to achieve a newly conceived purpose.

STANDARDIZATION.

It was recognized that the complete standardization of the automatic system for Post Office use could not be effected in a single step without long initial delay

and the temporary paralysis of some of our sources of supply. The most pressing need was to secure that all future automatic exchanges should be of such design that they would be able to intercommunicate directly one with another, without requiring the addition of any special devices or circuit complications for the purpose. First attention was therefore given to the standardization of electrical circuits and operating currents for all inter-exchange purposes, and this has now been accomplished. Each contractor is allowed to supply plant of his own type of mechanical construction, but all types must be capable of operating in the prescribed manner on the circuits which represent, for the time being, the standard methods of fulfilling particular functions. It will therefore be possible to equip any area, large or small, with exchanges supplied by any contractors who may, from time to time, secure the orders for their installation. The subscribers' automatic telephone and calling dial, and the operating impulses sent therefrom, are rigidly standardized, and the same applies to all trains of operating impulses and controlling or signalling currents sent from one exchange to another. Much progress has also been made in the standardization of the circuits which are purely internal to an exchange and do not affect intercommunication with its neighbours. All our contractors are also encouraged to unify the details of the mechanical construction of their apparatus as much as possible, with a view to the gradual evolution of a fully standardized Post Office automatic system. Such standardization has, of course, nothing whatever to do with any ideas of finality or fixation of practice. It simply means that at any given moment there is one standard way of making or doing any given thing. Improvements emanating from any source can be studied and introduced, not in partial and possibly conflicting ways as in a divergent collection of systems, but on a systematic general basis which greatly facilitates effective progress.

The first standardization study soon narrowed itself down to a choice among various important features in which the systems of the Automatic Telephone Manufacturing Co. and of Messrs. Siemens Brothers differed from each other. These features could not, as a rule, be considered independently; to a great extent the adoption of one dictates the adoption of one or more of the others. The decisions on the points at issue were as follows:—

(1) Impulses over junction circuits to be signalled round the loop, and not over one earthed conductor.
(2) Supervisory signals to manual exchanges and auto-manual positions to be sent by reversal of battery.
(3) Subscribers' talking and signalling current to be fed to the loop at final selectors, or at outgoing junction repeaters.
(4) Main battery to have E.M.F. of 50 volts (25 cells).
(5) Registration on subscribers' meters to be effected by means of a "booster" battery.
(6) Subscribers' lines to enter via 25-point rotary line switches having a "home" position and 24 outlets to selectors.
(7) The "private" banks on the levels of group selectors to have 11 points.
(8) The "busy" test on private bank contacts to be provided by an earth connection.
(9) Trunk-hunting switches to be stepped forward by individual, self-controlled drive.

Six of these points (1, 2, 3, 4, 8 and 9) represent the established practice of the Automatic Telephone Manufacturing Co.

With regard to point (5), the Department's experience with the Automatic Telephone Manufacturing Co.'s standard system of registration—by means of an electro-polarized relay operated by reversal of current when the called subscriber replies—indicates that, although accurate, it requires special testing and voltage-regulation plant to maintain it. For "booster battery metering," which has been adopted as preferable, the subscriber's meter, with the normal exchange voltage behind it, is wired to the "private" or test wire at the subscriber's rotary line switch. The meter is designed not to operate on this voltage. The "test" wire is linked up successively throughout all the switches used in a connection up to the final selector in the case of a local call, or to the outgoing circuit repeater in the case of a junction call. When the called subscriber replies, the operation of relays at the final selector or repeater applies a separate booster battery of 50 volts to the "test" wire in series with the main battery for about ½ second. The meter operates on this and its armature remains attracted on the normal battery voltage—the test wire being normally earthed at the final selector or repeater. It is confidently expected that this method will give complete immunity from false registration.

It should be mentioned that in "director" areas a simpler method of operating the subscriber's meter is practicable and has been adopted. In such areas the first selector switch, which is next in the train of switches to the calling subscriber's rotary line switch and meter, contains a relay operated by the reply of the called subscriber. A separate conductor can therefore be provided, at little cost, between the two switches, enabling metering to be effected by the simple closure of the meter circuit when the called subscriber answers.

The use of subscribers' rotary line switches with a "home" position—point (6)—is made necessary by the system of grading the outlets from the line switch banks to the first selectors. With graded outlets it is, of course, necessary that search over a level shall always start from the first outlet on that level.

The use of an 11th contact on selector levels—point (7)—is dictated by the desire to obtain traffic overflow measurements on each working level.

As soon as the leading characteristics of the general system had thus been determined the process of assimilating it to the director method of operation, and of designing the circuits and plant layout for all classes of service, began. For many months the engineers and traffic experts of the Post Office automatic group

were engaged in almost daily discussions with the engineers of the four large contracting companies who are responsible for the manufacture and installation of the exchange plant. The matter involves the consideration of masses of meticulous technical details, and great numbers of proposals and devices have been suggested, considered, tried out, and accepted or rejected. This work is now complete, so far as the initial system is concerned. Equipment for several large exchanges is now in course of manufacture, and in the cases of the Holborn exchange and the mechanical tandem exchange the work of installation *in situ* has been commenced. It may be mentioned that it takes, under present conditions, about 6 months to plan the traffic and engineering details of a large automatic exchange, about 12 months to manufacture it, and a further 12 months, or more, to install it in position and tune up its circuits for service.

In a field in which invention has been so rich as in that of automatic telephony, it is impossible to choose and stardardize a single system without a certain measure of regret that features of great interest and utility associated with other systems have necessarily to be sacrificed. The facilities for large group selection which are inherent in the panel system were not given up without reluctance, although it is believed that an excellent substitute for them is provided in association with the step-by-step system by the methods of grading smaller groups of outlets and, if necessary, interpolating additional trunk-hunting switches, as already referred to. The "rotary" system of the Western Electric Co. also includes many attractive features which are not applicable to the selected system. The same applies to the striking machine-driven system recently introduced by Messrs. Ericsson of Stockholm and now installed at Rotterdam and elsewhere. The 500-point selector switches of this system and the method of constructing its multiple fields are of great interest to telephone engineers. The Relay Automatic Telephone Co.'s system had also shown itself to be a convenient and economical system, at least for the smaller exchanges. But these systems all differ fundamentally from the step-by-step system and could only be made to intercommunicate with it by the addition of costly and complex special devices for interchanging traffic. The inherent complexity of even a perfectly uniform automatic system serving a large area is necessarily such that any deliberate policy of including in it exchanges of radically different type could not be entertained.

I am far from asserting that the London system will, in 20 years' time, necessarily stand as a model for the world to copy, but I am confident that the adoption of the step-by-step system, with the notable addition of the automatic "director" and other technical developments as worked out for London, represents the most practically suitable and effective way in which the telephonic needs of the next generation can be met in that great and important area.

It is understood that it has now been decided to install a step-by-step automatic system in Berlin, and that the same applies to the system of reconstructed exchanges which will replace those recently destroyed by the earthquake in Tokio.

(10) The Automatic Electric Company's "Director" System.

It has already been mentioned that the addition of the "director" to the long-established Strowger automatic system has endowed that system with facilities which enable any required connection to be set up by means of trains of controlling impulses having no necessary relationship with the impulses sent in from the calling dial of the originating subscriber.

The function of the director is to receive and store the call in its original form, and to proceed to send it out into the exchange switching mechanism, translated into any trains of impulses which may be required by the existing layout of junction routes and switching centres, to steer the call through, link by link, to the line of the required subscriber. As soon as the required connection has been established, the director disconnects itself from the line and becomes available for other calls.

The London subscriber's calling dial will carry a combination of letters and digits similar to that already referred to in connection with the panel system, and the arrangement of exchange names and numbers in the telephone directory will also be identical with that adopted for the panel system.

It should be noted here that the translation effected by the director applies not only to the number of impulses in a train but also to the number of trains sent. The subscriber will be required to signal 3 letters and 4 digits for each call, but the director can transform these 7 impulse trains into any number of directive trains from 5 to 10. This attainable maximum provides more than adequately for any possible future requirement of the London system, or any other system.

The director consists of 9 switches with associated relays and a cross-connecting field. Two switches are of the usual Strowger type having vertical and horizontal movements; these are designated the "A" switch and "BC" switch respectively. Two switches are of the pre-selector type and are designated the "sending switch" and the "sending control switch." Five switches, designated "minor switches," are practically small Strowger switches with rotary movements only. Four of these switches are used as digit-storing registers and one as an impulse distributor.

The "A" digit switches are grouped on separate racks and do not form part of the assembly of an individual director, which includes all the other pieces of apparatus mentioned, mounted on a rectangular frame measuring about 24 in. × 18 in. (see Fig. 19).

The "A" digit switch receives the first train of impulses dialled by the subscribers, which corresponds to the first code letter of the exchange required. Each level of the "A" switch is associated with a separate group of directors set apart for effecting connections with exchanges having names commencing with the same, or an equivalent, letter, and the "A" switch, having been dialled to a particular level, searches to find the "BC" switch of a free director on that level.

The second and third trains of dialled impulses are received by the "BC" switch; the second train lifts the switch brushes to one of the 10 levels, and the third

train rotates the brushes to a particular set of contacts on that level. The "BC" switch is equipped with 6 brushes and 6 separate sets of bank contacts. Thus the dialling of the second and third of the three initial or "code" letters of the required exchange has set the "BC" switch of a director in a particular group to 6 particular multipled contacts, and has closed 6 circuits which will always be closed by any subscriber who dials that exchange code. The 6 circuits thus set up, when suitably cross-connected, enable the switches of the director to send out any desired number of trains of impulses from 1 to 6 (each train consisting of any number of impulses from 1 to 10) and so steer appropriate group (ABC = level 2; DEF = level 3, etc.).

The directors of each group are capable of serving 81 exchanges, and as 8 group levels are available on the "A" switch the total number of exchanges which could be served without mechanical modification of the directors is 648. This is so far above the number of exchanges ultimately required in London that the cross-connection field has been designed to serve 35 exchanges in each director group, or a total of 280. Even with this reduced number abundant spare space can be left, on the directors appropriated to each three initial letters, to avoid any restriction in the choice of

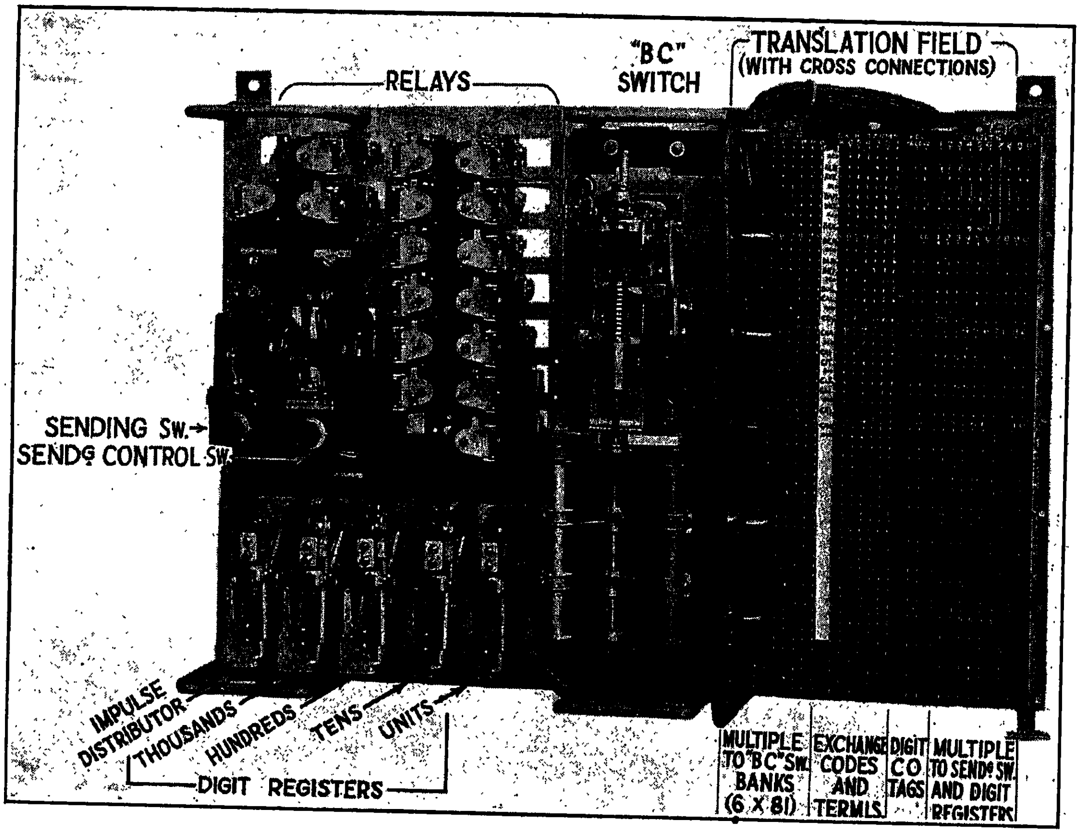

FIG. 19.—View of director assembly.

the call by its prescribed route to any required exchange, where the direct operation of the final 4 trains, representing the numerical digits of the dialled number, will reach the line of the called subscriber.

It will be noticed that the initial letter of the exchange code—absorbed in the "A" digit switch—does not pass into the director and is not subjected to translation. It is found that the total quantity of apparatus required can be reduced by confining translation to the second and third code digits, and setting apart a group of directors to handle calls for the exchanges having initial letters with the same numerical equivalent. The first train of impulses is therefore used to select the level of the "A" switch which gives access to the exchange names on that account, although such restriction could easily be applied if necessary.

Under average conditions a director to which properly graded access is provided will carry about 72 calls in the busy hour and will be occupied with each for about 20 seconds. To serve a busy city exchange the installation of from 150 to 180 directors is necessary.

The operation of the director can be examined in more detail with the aid of Fig. 20. The subscriber on lifting his receiver obtains, via the bank of his rotary line switch, a first code switch in the ordinary exchange system, and at the same time the "A" switch-finder hunts to find a free "A" switch, from which the subscriber receives the "dial" tone informing him that

he may proceed to turn in the call. Suppose the subscriber wants the "Avenue" exchange and dials AVE 2468, which corresponds to 283 2468. The A is received by the "A" switch, the brushes of which are lifted to the second (or ABC) level, and a free "BC" switch in the group of directors associated with that level is found.

The train of 8 impulses corresponding to V is dialled into the vertical magnet of the "BC" switch, via the impulse distributor, the two brushes of which are standing on the first pair of contacts. At the end of this train the impulse distributor takes one step, and the train of 3 impulses, corresponding to E, are received by the horizontal magnet of the "BC" switch. The six brushes of the "BC" switch are now set on the third contact of the eighth level in each bank. The impulse distributor brushes now step to its third pair of contacts.

Dialling proceeds and the trains of dialled impulses representing the called subscriber's number are successively routed by the impulse distributor to the four digit registers which are set in the positions 2 on the thousands register, 4 on the hundreds register, 6 on the tens register and 8 on the units register. The call has now been received and stored in the director, but before this operation is complete the process of sending it forward in its transformed shape has already been begun.

It may be assumed that direct junctions to the Avenue exchange can be reached through two ranks of code switches at the originating exchange and that the translation in the director required to set up these switches is to be "2, 6." That is to say, only two trains of impulses are required, out of the possible six trains provided for, via the six brush circuits of the "BC" switch. If additional ranks of code switches at an intermediate switching centre had been involved, a correspondingly greater number of trains would have been necessary. The translation is effected by cross-connecting the first of the particular six bank contacts of the "BC" switch to contact No. 2 of the "sending switch" bank, and the second bank contact of the "BC" switch to contact No. 6 of the sending switch. The superfluous bank contacts (Nos. 3, 4, 5 and 6) of the "BC" switch will be connected to the "sending control switch," via the terminal marked "D.C.O." (digit cut-off), in order to step that switch to the correct position for discharging the digit registers at the proper moment.

After the three code letters have been dialled in, the impulse distributor brushes will have moved to the third pair of contacts and the sending control switch will be standing on its first contact. The earth-connected brush of the impulse distributor will therefore complete a circuit, via brush 1 of the "BC" switch and the cross-connection, to contact No. 2 of the

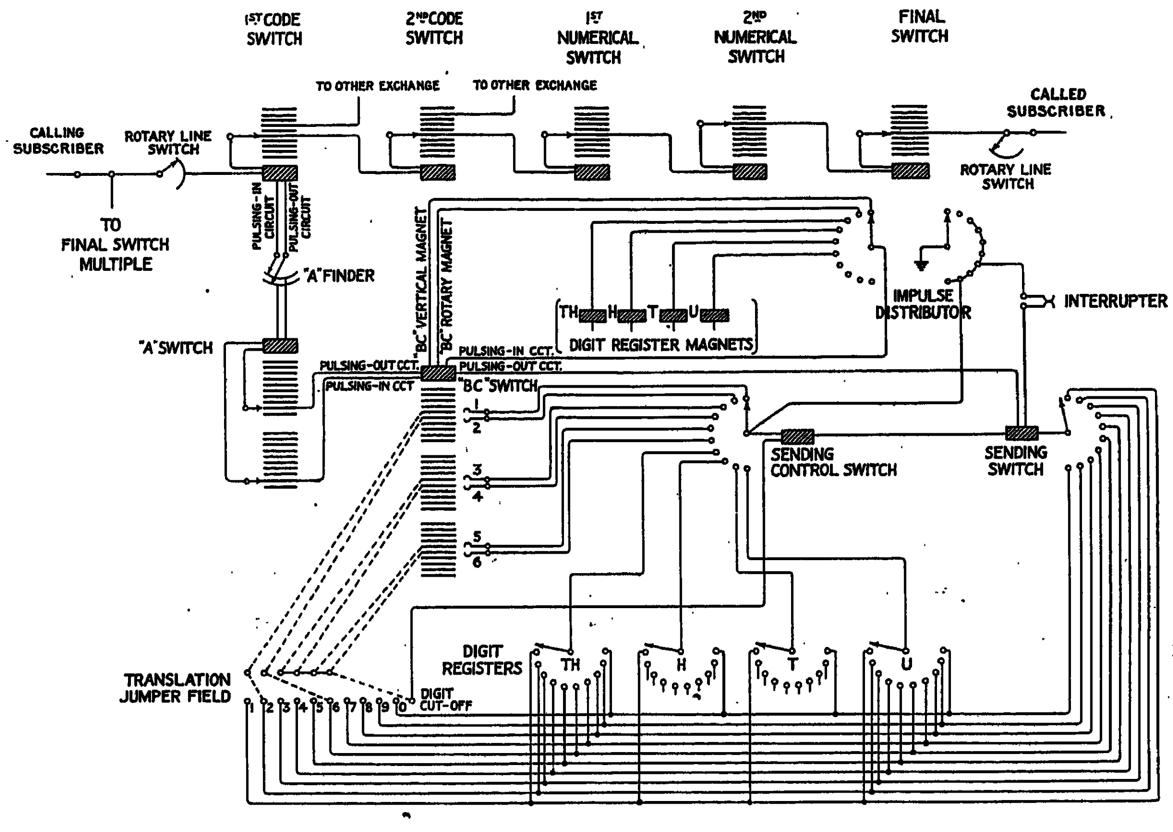

FIG. 20.—Principles of the director system.

"sending switch," which will thus be earthed. At the same moment the earth-connected brush completes a circuit, permitting impulses from the interrupter springs of a continuously running impulse machine to be directed to the sending switch magnet, and the switch begins to step over its contacts. At each step an impulse is sent to the first code switch over the "pulsing-out" circuit indicated in the figure. When the sending switch brush reaches its second contact, which has been "marked" by the sending control switch, it encounters the earth connection and a relay is operated which prevents further impulses from being sent to the first code switch. The sending control switch now steps forward to the second "BC" brush circuit and the sending switch returns to normal. Meantime the first code switch brushes have entered the second level of its bank contacts and found an outlet to a free second code switch.

The sending control switch brush, now standing on its second contact, makes an earth connection, via brush circuit No. 2 of the "BC" switch, with contact No. 6 of the sending switch. The sending switch again steps forward and now sends 6 impulses to the second code switch before its impulses are stopped by the earth on its contact No. 6. The second code switch brushes are stepped to level No. 6 and find a free line to the Avenue exchange, whilst the sending switch again returns to normal and the sending control switch steps to position No. 3. From this position it finds a circuit in turn, via brushes Nos. 3, 4, 5 and 6 of the "BC" switch, which represent superfluous translation circuits and have all been joined, by a cross-connecting wire, to the "digit cut-off" terminal. The brushes of the sending control switch are therefore carried straight forward to position No. 7. Positions 7, 8, 9 and 10 connect with the four "digit registers" on which the Avenue number of the called subscriber has been stored. From these positions the switch will now successively control the sending of the thousands, hundreds, tens, and units digits. As these do not require translation the banks of the digit registers are multipled directly to the sending switch. The impulses for these digits are sent out over the junction line to Avenue and set up the numerical switches at that exchange. Immediately after the units digit has been sent out from the director the latter is released from the first code switch, all its parts return to normal, and the calling subscriber is connected through to the final numerical switch at Avenue, from which the required subscriber is being rung.

The "pulsing-in" circuit over which the subscriber's impulses pass into the director remains entirely separated, at the first code switch, from the "pulsing-out" circuit over which the director passes forward the call through the code and numerical switches until the connection has been completely set up and the director has been dropped. Pulsing-out commences as soon as the exchange code portion of the number has been dialled in, i.e. as soon as the impulse distributor reaches its third contact and connects earth to the sending control switch and to the interrupter of the impulse machine. The periods of storing the call and of sending it forward thus overlap each other and the actual delay in establishing connection with the called subscriber is, on the average, only about 2 seconds greater than it would be if the call were dialled straight into the switches.

As a theoretical example of a more complex case of routing, involving the use of intermediate switching centres and the utilization of all the six available translation channels, it might be assumed that a call, say, from Ealing to Ilford, would be dealt with as follows:—The exchange code ILF (453) would have its second and third digits translated in the director to 234567. Digits 2 and 3 would operate first and second code selectors in Ealing, and gain access via an outgoing junction to a tandem selector in Holborn. Digits 4 and 5 would operate first and second tandem selectors in Holborn and reach a tandem selector in Maryland. Digits 6 and 7 would operate first and second tandem selectors in Maryland and reach a first numerical selector in Ilford. The four untranslated numerical digits of the subscriber's number would then follow and effect connection with the called line via the first and second numerical selector, and a final selector, at Ilford.

The actual circuit arrangement of the director system is necessarily somewhat complex, and a discussion of it in any detail is not within the scope of this paper. (Mention should, however, be made of an innovation as regards the position of the battery feed to the calling subscribers. Hitherto on the Automatic Telephone Manufacturing Co.'s system this has always been located either at the final numerical switch or on the outgoing junction repeater. In the director system as adopted by the Post Office it will be located at the first code switch, thereby rendering outgoing junction repeaters unnecessary, except on tandem routes, and effecting a very appreciable economy in London and other large areas where the percentage of junction traffic is large.)

Director Translations.

Fig. 21 is a sketch of the arrangement of the translation jumper field. On the left of the drawing six sets of bank contacts each connected to a set of 81 terminals are indicated. Each of these six sets of terminals reproduces the bank contacts of the "BC" switch corresponding to each of the six brushes and is wired out to these terminals as indicated by the brush, or "wiper," numbers.

Levels 2 to 0 and contacts 2 to 0 on each level only are so wired out, level 1 and contact 1 being omitted since there are no letters equivalent to digit 1 on the lettered dial. At the centre of the assembly there are 35 sets of six exchange terminals, each set being labelled with an exchange name and wired to the tags representing the positions on which the six brushes rest when the code of that exchange has been dialled into the "BC" switch. Between every two sets of exchange terminals one set of D.C.O. (digit cut-off) terminals is fitted. On the right-hand side are 36 sets of digit terminals numbered 1 to 0, each vertical row of which represents one of the 10 bank contacts on the sending switch and digit registers.

Cross-connections are made between the six exchange

terminals and the 10 digit terminals as required to give the desired translation.

The terminals marked "CO" are used for clearing the director when it is required to route a call by code translation only, without numerical digits. Certain service calls will be dealt with in this manner.

The terminals marked "OPER" are used to route a call to an operator after the dialling of digit 0 by the subscriber. Such a call will find a director but will

(1) *Subscriber to subscriber calls* (subscriber dials 3 code and 4 numerical symbols).

(*a*) *Translated to* 1 *code selection, followed by* 4 *numericals*, e.g. if the subscriber dials "AVE" 1234, the "AVE" exchange terminals will be connected as follows:—

Terminal 1 will be jumpered to the digit terminal corresponding to the pulses required to be sent to the code selectors.

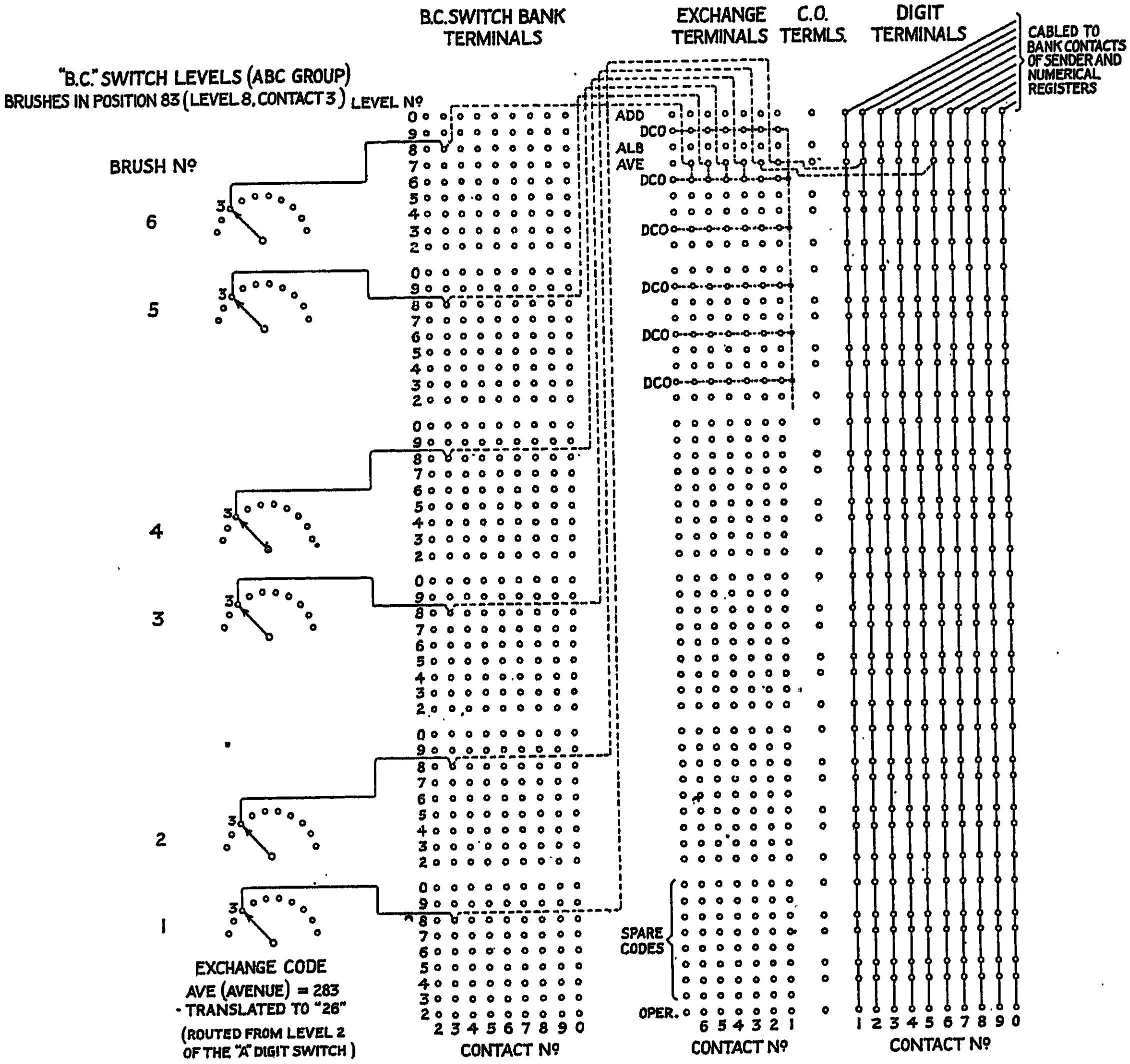

FIG. 21.—Diagram showing arrangement of translation jumper field of director in 200 (ABC) group.

not operate the "BC" switch. A special relay, operated on 0 level calls only, is introduced into the director and sets up connections similar to a setting of the "BC" switch brushes, giving at once the desired translation. Arrangements are such that any predetermined director in any group can be reached from the 0 level of the "A" digit switch for this service.

The various cross-connections used to give the different services required may be briefly summed up as follows:—

Terminals 2, 3, 4, 5 and 6 will be connected to the nearest "D.C.O." terminals.

The numerical digits will be repeated as dialled into the digit registers by the calling subscriber.

(*b*) *Translated to* 2, 3, 4, *or* 5 *code selections, followed by* 4 *numericals*.—The same method is followed as under (*a*), i.e. exchange code terminals are jumpered to the digit terminals required. The unused exchange terminals are always connected to the nearest "D.C.O." terminals.

The numerical digits are repeated as dialled.

(*c*) *Translated to 6 code selections, followed by 4 numericals.*—The same method is followed as under (*a*), i.e. exchange code terminals are jumpered to the digit terminals required. As all the exchange terminals are thus used, no connection to the " D.C.O." terminals is required.

exchange terminals designated " OPER " are jumpered as described under 2 (*a*) above.

(3) *Vacant exchange codes.*

All vacant exchange code terminals associated with wiper 1 (only) are " commoned " and jumpered to the nearest " SC, " i.e." spare code " terminal. The dialling of one of these dead exchange codes causes the director

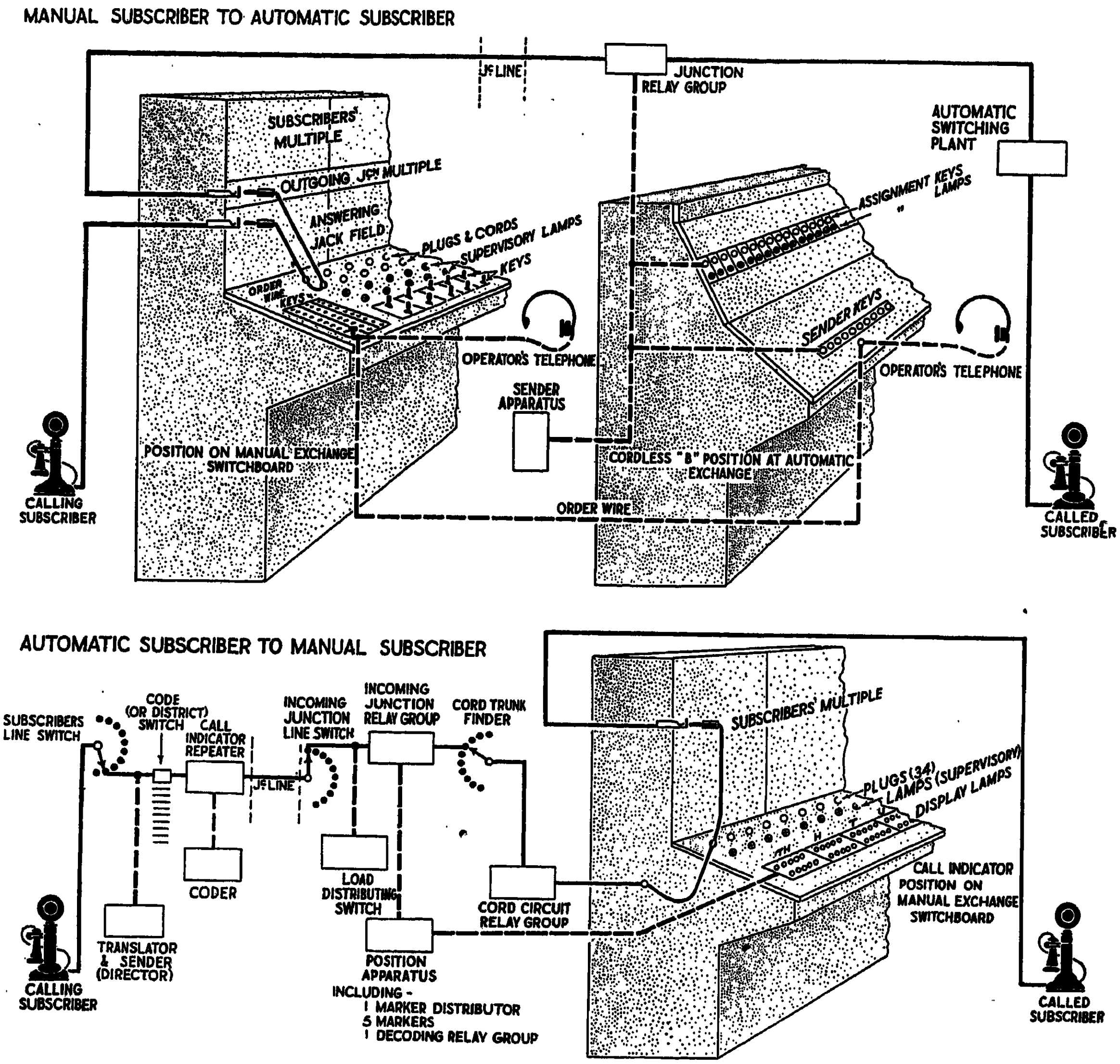

FIG. 22.—Diagram of call indicator transfer method.

(2) *Special service calls.*

(*a*) *Subscriber dials special service 3-letter code,* not followed by numericals, e.g. TOL. The same method is followed as under 1 (*a*) or 1 (*b*), i.e. the exchange code terminals are jumpered to the digit terminals necessary to route the call to the destination required. The first unused exchange terminal is jumpered to the nearest " C.O." terminal instead of the " D.C.O." terminal, and the remaining terminals are left disconnected.

(*b*) *Calls to operator* (*subscriber dials* " 0 ").—The

to be released immediately the third code digit is dialled, and the subscriber receives the " number unobtainable " tone signal.

Call Indicator Working.

Until the conversion of London to automatic working is fully completed, which may occupy a period of from 15 to 20 years, manual working will exist side by side with automatic working and arrangements are necessary to ensure smooth operation between the two systems during the interim period.

Traffic from automatic to manual exchanges will be handled by means of " call indicator " positions at the manual exchange, as illustrated in Fig. 22. The automatic subscriber will manipulate his calling dial in an identical manner for all calls. If the call be for a manual exchange the operation of the three initial letters of the exchange name will steer the call through to an available incoming junction operator's position at that exchange, and the further operation of the four numerical digits will cause the required subscriber's number to appear visually on a " call indicator " in front of the junction operator. This operator will, without speaking to the calling subscriber, connect the circuit manually to the required subscriber's line. She may use any one of her plugs and cords for this purpose ; the act of plugging into the subscriber's line jack brings into operation a " cord trunk finder " which connects the plug and cord to the junction upon which the displayed number has been pulsed.

In the converse case for a subscriber connected to an exchange not yet converted to automatic working, two methods are available by which the manual exchange operator may deal with the call if connection with a subscriber on an automatic exchange has been asked

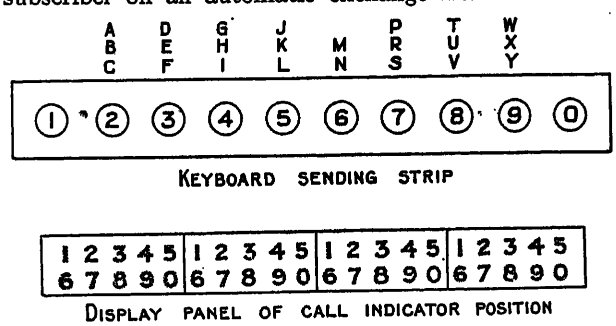

FIG. 23.—Key sender and call indicator.

for. The first method (see Fig. 22) provides that she shall pass forward the call verbally, by order wire, to an incoming junction operator at a special " B " switchboard in the automatic exchange. The latter operator will assign a junction circuit, by pressing an assignment key, and will set up the call by means of a set of plunger keys known as a key sender. The automatic plant does the rest and clears the key sender for further use as soon as the call has been steered through to its destination.

In the second method the operator who answers the call from the subscriber at the manual exchange is herself provided with sets of key senders, on one of which she can set up the call and so direct it forward through the automatic plant at the distant exchange to the required subscriber's line, without the co-operation of a junction operator. The adoption of one or the other method depends upon the local conditions at the exchanges in the area, but the first method, which avoids the need for special equipment at the answering operators' positions, is generally to be preferred and has been adopted for London. Fig. 23 shows the arrangement of keys on the key senders, and illustrates the manner in which the called number is displayed visually on the call indicator.

In its operating principles the system of " call indicator " working adopted for London is similar to that invented for use in connection with the panel system, but the London system contains several novel features which warrant a further brief reference. It is termed by the Automatic Telephone Manufacturing Co. a " coder call indicator system " and its object is to minimize the number of automatic switches necessary to display a call at a manual exchange, and to provide facilities for even traffic distribution of calls from all exchanges among the operators. Its operation is briefly as follows :—

At the originating automatic exchange the director impulses, instead of passing directly to line and to the distant exchange from the outgoing switch, are stored in the relays of an equipment assembly termed a " coder," which is at the same time connected to the junction line. At the manual exchange the connection of the coder to the line at the distant end routes the line to a set of incoming " decoder " relays by means of a " marker " controlled by a " marker distributor." Five markers and one marker distributor are provided for each call indicator position. When the junction line had been routed to the de-coder of the call indicator position the coder at the originating end is permitted to discharge. The decimal settings of the coder relays are translated and transmitted over the line as coded impulses of positive, light negative, and heavy negative currents, and stored in the de-coder relays. As soon as the display lamps are freed from the previous call this setting is transferred to a group of numerical relays which cause the called number to be displayed by the lamps in the display panel in the usual way. The arrangements are such that while one call is on display at each position, an indefinite number may be stored on coders at the automatic exchange. Whilst one call is being displayed, five markers per position will be connected to junction lines associated with an equal number of waiting coders, and the traffic will thus be kept in order of priority.

The discharge of the coders into the de-coding relays occupies 1 second, and transference from the de-coder to the display panel is immediate.

At the manual exchange, traffic reaches the positions in cyclic disengaged order in quantities that correspond to the operators' abilities, and in queue formation at each position. Positions at which either all receiving relay sets or markers are engaged are treated as busy and passed by the marker distributor. A call displayed on the display panel is not directly associated with any one cord circuit on the position. The plugging-in of any idle cord to the multiple jack of the required number immediately starts a finder switch, which hunts for the calling line, connects the cord to it, and switches out the lamps on the display panel.

The cords are not normally used for the completion of service calls. Such calls are operated by the depression of a service key which causes a finder switch to hunt for the calling line and connect it to a service operator's position. Busy calls receive the engaged tone by the operation of a key in a similar manner. This reduces the number of cords required, and is a factor of value in some cases where the cord capacity of manual exchange " B " positions is restricted.

Each call indicator position is equipped with 36 cord circuits and it is expected that each operator will handle 450 calls during the busy hour. This is probably a conservative estimate.

It will be appreciated that before the first equipped automatic exchange can be brought into use the whole of the existing manual exchanges in London must be equipped for call indicator working. It follows, therefore, that during the initial stages of automatic working over 90 per cent of the automatically originated inter-exchange traffic in London will be handled at call indicator positions. This percentage will gradually decrease as more automatic exchanges are brought into use, and will finally be extinguished. An automatic subscriber, however, apart from any local knowledge which he may possess, will be quite in ignorance as to whether his call is going to another automatic exchange or to a manual exchange. His operations will be alike in both cases—he will dial three code letters and four digits, and in both cases he will receive the same tones, etc., to indicate to him the progress of his call. When complete conversion to automatic working has been effected, the whole of the call indicator equipment will have disappeared, together with all coder equipments at the automatic exchanges themselves.

It may be urged that this method of tackling the problem is wasteful, inasmuch as call indicator equipments will be progressively thrown out of service during the period of transition. An obvious alternative would be to install automatic equipment at each manual exchange, of a capacity sufficient to deal with the incoming junction traffic and having the subscribers' lines multiplied on the final selectors in parallel with the multiple on the manual board. Then when the time arrives to convert the manual exchange to full automatic working the automatic plant already installed could be worked into the full scheme at that or another exchange and little wastage of plant would result. The possibilities of this scheme were fully considered, but serious objections to its adoption revealed themselves. These arose mainly from the lack of adequate building accommodation for the interim automatic plant, from the extensive changes to subscribers' numbers to provide for automatic private branch exchange service which would be immediately necessary, and from the need for expensive additions to the manual exchange power plant in order to permit the use of standard 50-volt automatic switches. Considerable difficulty has, in fact, been experienced in many cases in finding adequate accommodation for the plant required at manual exchanges for the call indicator equipment, although the space required is much less than that needed for the alternative scheme.

Moreover, the wastage of call indicator apparatus will be minimized by the use in other large areas such as Manchester, Birmingham and Liverpool, of equipment recovered from London exchanges, and probably much of it will remain in service during the greater part of its economic life.

Cordless "B" Positions.

Traffic originated at a manual exchange for an automatic exchange can be handled in two different ways, as already indicated. In the method adopted, each automatic exchange is equipped with special manual "B" positions and demands are passed, by order wire, to these positions from the "A" operators at the originating manual exchange. The operating procedure at the "A" positions is identical with the procedure to manual exchange "B" positions. The "B" operator at the automatic exchange sets up the call on the automatic switches by means of key sending equipment. As this operator is not required to handle any other class of traffic, key sending equipment is used in preference to dials, since quicker and more efficient operating is obtained thereby.

The other of these alternative methods would require that all manual exchange "A" positions in London should be equipped with dials and dial keys, and, since it would not be possible in many cases to dial from the manual exchange cord circuits directly into the automatic switches, it would be necessary to equip most of the incoming junction lines with "dialling-in" repeaters at the automatic exchange. Further, the increased amount of operating per call at the "A" positions would so increase the operators' load that a large number of additional "A" positions would be required in London to handle the volume of traffic during the busy hour. The cost of adopting this alternative, without serious interruption to service, would be so great, as compared with the cost of the method adopted, that the latter was preferred without hesitation.

In order to cater for traffic from manual exchanges, each automatic exchange will therefore be equipped at the outset with a suite of cordless "B" positions equipped with key senders (see Fig. 22). The key sending equipment consists of a strip of digit keys associated with four sender finders which route the digit keys to a free sender. The registers which are wired to the bank contacts of the sender finder consist of four groups of four relays, one group for each digit. These relays are operated by the digit keys either singly or in combinations of twos or threes to obtain all digits from 1 to 0. The setting of the relays determines the "marking" of a contact on the sender switch by means of which impulses are sent out to the exchange numerical switches in a manner very similar to the method used for sending out the numerical impulses from the director.

The junctions from the manual exchange are brought through the cordless "B" position and carried on to a first numerical switch on which they terminate. At the position each junction is associated with a group of relays, and an assignment key and lamp for each junction are fitted as part of the face equipment of the position. The operating procedure is simple and is as follows:—

The "A" operator at the manual exchange passes a demand by order wire to the cordless "B" operator. The latter allots a junction and immediately depresses the assignment key of the allotted line. This causes the allotted junction and the operator's digit keys to be connected to a free sender with associated registers. The operator then depresses in proper sequence the four digit keys corresponding to the four figures of the called subscriber's number. These four figures are routed by means of a control switch to the four groups

of register relays, which are operated and locked in the proper combination simultaneously with the depression of the digit keys. (After the depression of the last key—the fourth—the set is at once available for another call.) The bank contacts of the sender switch are thereby marked and impulses are sent out to the numerical switches. Sending cannot commence, however, until the operator at the manual exchange has taken the allotted junction line. When all sending is finished the sender and registers are disconnected from the junction line and the latter is switched through, via the numerical switches, to the called line.

A supervisory lamp is associated with each junction line at the cordless "B" position. After depression of the assignment key on an allotted junction the operator must not proceed with the setting up of the required number on her digit key strip until a signal is received on this lamp to indicate that a free sender has been found. The provision of senders is on such a basis that no delay is likely to occur at this stage. The supervisory lamp will flash until the originating "A" operator takes the allotted line, after which it will glow continuously until the "A" operator clears at the end of a conversation.

Should the "A" operator connect to a line other than that allotted, the supervisory lamp on that line will flicker rapidly to indicate to the "B" operator that a wrong connection has been set up.

Centralization of Manual Boards.

When sufficient automatic exchanges in London are in use the cordless "B" positions and special "A" positions for operator service, etc., instead of being equipped in each automatic exchange, will be centralized, the centres being so chosen, to serve a group of adjacent exchanges, that economical use of line plant is achieved. There will be a number of such manual centres in London when the automatic traffic in the individual areas has reached a certain density. Great advantages in the design and cost of automatic exchange buildings will result from the centralization of manual board traffic, since these buildings will not be required to accommodate the manual switchroom and operators' quarters.

The Mechanical Tandem Exchange.

In the London area there are a large number of comparatively small exchanges with small groups of junction lines to and from each of the larger exchanges.

As a result of the traffic inefficiency of small groups, and of the fact that order-wire working is ruled out, the busy-hour loads carried by these junctions are very low and their operation is uneconomical. Frequent consideration has therefore been given to the introduction of one or more tandem junction exchanges, at which all the junctions to and from each small exchange could be concentrated and thus form a group suitable for order-wire working. Such a scheme could not, however, be shown to possess any economic advantage, on account of the cost of introducing a third operator on each tandem connection. The development of the automatic call indicator scheme increased the possible speed of operating and so favoured the introduction of tandem junction working, and the advantage of introducing automatic tandem switching plant was, naturally, considerably increased by the decision to adopt the automatic system at London local exchanges. The installation of a mechanical tandem exchange has therefore been pressed forward, in advance of the completion of the first local automatic exchanges.

The mechanical tandem exchange is now being installed in the same building as the Holborn automatic exchange. In it will be concentrated the outgoing and incoming junctions from the smaller exchanges as well as a number of junctions to practically all the other London exchanges.

At the beginning of its life, and for the period which will elapse before conversion to automatic working in London is completed, the mechanical tandem exchange will be required to route traffic as follows:—

From manual exchange to manual exchange.
From manual exchange to automatic exchange.
From automatic exchange to automatic exchange.
From automatic exchange to manual exchange.

The method of handling this traffic is indicated by Fig. 24. Traffic from the "A" positions of a manual exchange will be dealt with in a similar manner to the traffic incoming to a cordless "B" position at an automatic exchange. The "A" operator will "order wire" the call to the cordless "B" operator at the tandem exchange, who will set up the call to the automatic switches via her key sender. In this case, however, since the exchange code must be set up in addition to the subscriber's number, the sender is associated with a translating unit, similar in principle to the director, and with a coder. If the call is for a manual exchange it will be directed to a call indicator position at that exchange, and the numerical portion of the required number—transformed into the correct impulses by the coder at the mechanical tandem exchange—will effect the required display on the lamp panel at the call indicator position. If, however, the call is for an automatic exchange the cross-connections in the translator jumper field will be such as to suppress the operation of the coder, and the numerical digits will go out to the switches at the automatic exchange in the regular manner.

Traffic originated in an automatic exchange will be carried direct from the levels of the outgoing switches to the first tandem switches at the mechanical tandem exchange. In the case of a call for a manual exchange a coder—interposed between the manual levels on the first tandem switches and the second tandem switches—will come into operation as soon as the second tandem switch has been operated, and the numerical portion of the required number will be stored in the coder and converted, as already described, for display at the call indicator position. A call for another automatic exchange will pass out via levels on the first tandem switches which are not equipped with coders, and the call will be routed straight through the switches as determined by the impulses from the director at the originating automatic exchange.

As the conversion of London to automatic working proceeds, the traffic incoming to the mechanical tandem exchange from manual exchanges, and the traffic outgoing to call indicator positions, will decrease and will ultimately fall to zero. The whole of the traffic will then be purely automatic and will be routed direct through the switches, as at other main switching centres in the London system. The cordless "B" positions and their equipment will no longer be required for their original purpose, and it will probably be desirable to utilize them for passing traffic from towns in the London toll area into the automatic system. This question will be considered in due course, as the cordless "B" positions at the mechanical tandem exchange are freed from local traffic.

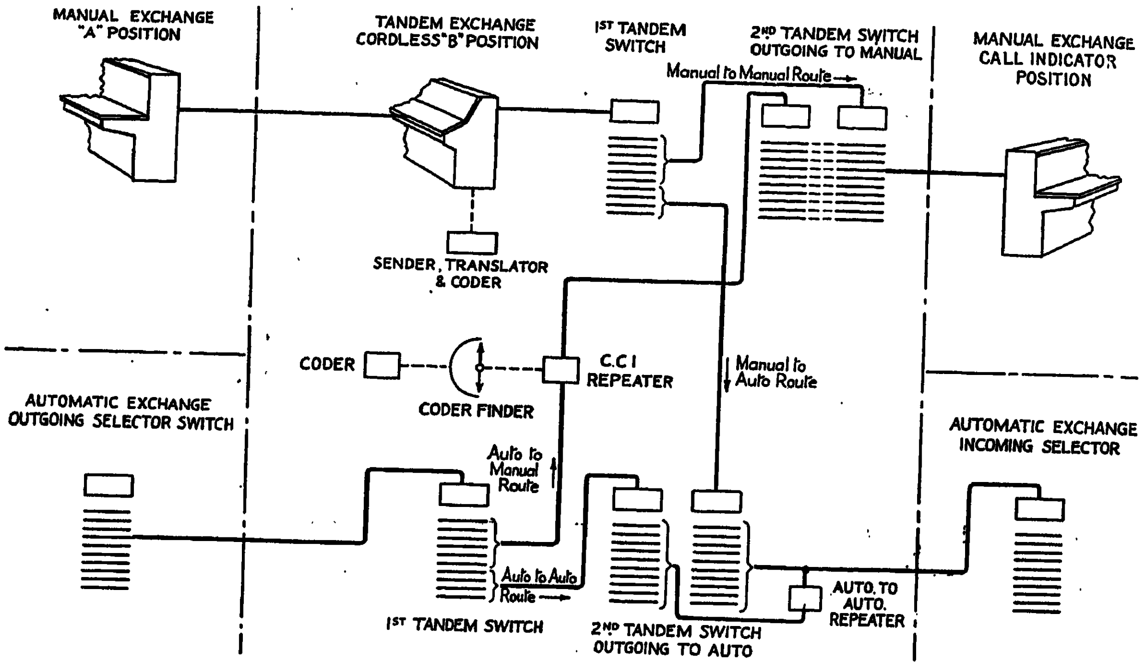

FIG. 24.—Mechanical tandem routing scheme.

Power Consumption.

At a city exchange of approximately 10 000 lines, and at the mechanical tandem exchange, the operating current at peak load will exceed 2 500 amperes. Two sets of 50-volt storage batteries, each having a capacity of 10 000 ampere-hours, are provided. During busy hours the load on the batteries is eased by running the charging machines in parallel with them.

Various Classes of Services Provided.

The subscribers connected to an automatic exchange will be divided into two groups: (a) those to whom trunk calls are permitted and (b) those to whom trunk calls are barred. The distinction is of course of the subscribers' own seeking, but it is necessary that the department should guard itself against improper use of the trunk lines by those subscribers who are not entitled to this service. A subscriber who requires a trunk connection will dial TRU if on a director exchange. (The letter "O" is used for this purpose at non-director exchanges in the provinces.) In the group where trunk calls are permitted the call will be routed to a record operator, but in the group where such calls are barred the call, if made, will be routed to a special operator and dealt with accordingly.

Subject to this restriction the following classes of service will be provided:—

Subscriber to subscriber—direct.
Subscriber to subscriber—over junction circuits.
Subscriber to subscriber—over trunk lines ("revertive" calls).
Subscriber to subscriber—over toll lines ("no delay" calls).

Coin-box stations and call offices to and from all other subscribers in the system direct, or over junction, trunk, or toll lines.

Private branch exchange traffic with night traffic on selected lines in each group of exchange lines.

Inquiry, information, and directory services.

Dictating messages for onward transmission as telegrams, express letters, or letters.

Receiving telegrams in lieu of delivery by messenger.

Calling for the services of express messengers.

Tone Signals.

A system of tone signals designed to give a calling subscriber knowledge of the progress of his call has been standardized for use in both London and the provinces. Before commencing to operate his calling dial the subscriber should listen for a "dial signal tone," which indicates that a free selector in the first

rank—or, in London, an "A" digit switch—is available to receive the dialled impulses. Dialling must not commence until this tone—which is continuous at a frequency of 33 per second—has been received.

If the called subscriber's line is engaged, or if, at any stage of the call, all outlets from a selector switch level are busy, a "busy tone" will be sent out. This tone has a frequency of 400 per second and is applied for "off and on" periods of 0·75 sec. The tone is associated with a flashing signal on the supervisory lamp of an operator's cord circuit in the case of a call from a manual exchange subscriber.

When dialling is completed the subscriber will immediately receive "ringing tone" to indicate that the required subscriber is being rung, or "busy tone" to indicate that he is already engaged. The ringing tone is provided by means of a leak from the ringing circuit through a condenser of small capacity on which current pulses at a frequency of 133 per second are superposed. This tone is applied to the line with the same interruptions as the ringing current itself, i.e. a double beat of 1 second with a 2-seconds' interval. The double beat consists of two rings of 0·4 second duration separated by an interval of 0·2 second.

In areas where the director is not used a further tone known as the "number unobtainable tone" is employed to indicate to the subscriber that he has dialled a ceased or unallotted number. In London this tone will be used to indicate to a subscriber that he has incompletely dialled the required number. Calls for ceased or unallotted numbers will be routed to an operator.

Alarms and Guarding Devices.

A complete system of alarm and guard devices is provided to facilitate supervision of the working of the exchange and to call immediate attention to any irregularity in the operation of the switches. The alarms are given by a lamp associated with a bell or buzzer and are divided into the following categories:—

(1) Individual switch alarms.
(2) Individual panel or shelf alarms.
(3) Individual rack alarms.
(4) Group alarms.

The alarms are operated in trains.

A fault or irregular condition which brings in an individual switch or panel alarm will also bring in the appropriate rack and group alarms. The maintenance officer will thus be guided from the group alarm to the rack alarm and then to the panel or switch on which the fault or irregular condition has occurred.

Switch alarms are provided on those switches which are normally connected with a subscriber's line by the act of lifting his receiver, without dialling. Such switches are the first group selectors in non-director areas and the first code switches in director areas. The alarm lamp will indicate in this case a loop on a subscriber's line and, should this loop persist for 3 minutes without impulses being dialled, a clock-controlled relay set will come into operation and cause the rack and group alarms to operate.

Individual switch lamps are also provided on the final selectors in non-director areas to call attention to the condition where a called subscriber's line is held after the termination of a conversation by the failure of the calling subscriber to restore his receiver. In director exchanges the corresponding lamp is provided at the first code selector.

On other ranks of switches the alarm lamps are provided on the basis of one lamp per panel or shelf of 20 switches. The most probable irregularity in the use of switches in these ranks is that they may be improperly held by a subscriber leaving his receiver off after incomplete dialling of the required number; this happens so rarely that alarms on the basis of one per switch would not be justified.

In addition to the foregoing supervisory alarms, signals are provided to call immediate attention to fuse failures and to "release" failures on switches of all ranks.

Private Branch Exchange Lines.

Most private branch exchanges have more than one line to the exchange and it is of course necessary to arrange that, if a call be received when the particular line representing the exchange number of the private branch exchange (PBX) is engaged, the calling subscriber shall not receive the "busy" signal unless all the lines to the PBX have been searched and also found to be engaged.

It is therefore necessary to arrange that the group of lines to a PBX shall be connected to consecutive positions on the bank multiple of the final switches and to provide all switches on which such groups of lines terminate with means for continuing their rotary motion as a hunting operation throughout the group—after the impulses of the units train have carried their brushes to the first line of the group—until an idle line is found, or the whole group has been searched without success.

Switches provided with this facility are known as "rotary final switches" or "rotary connectors." In the case of PBX groups of two or three lines no special difficulty arises, apart from the fact that all the lines must appear on one level of the switch and that a few spare positions for future growth must also be left upon that level. This tends to a certain amount of plant wastage, and also generally involves changing the exchange numbers of a proportion of the subscribers in order to get them properly grouped on the levels of the switches when a transfer to the automatic system is made.

When, however, the present or probable future requirements of a PBX exceed 10 lines, and therefore exceed the accommodation of a normal switch level, it is necessary to take special steps to ensure the availability of all the lines when a switch is hunting to complete a call for the PBX number. Line-hunting over groups up to 20 in number can be provided by utilizing rotary final switches having 10 double levels of 20 contacts. Each such level absorbs only 10 line numbers in the subscribers' multiple series, the remaining 10 having auxiliary numbers. This scheme is therefore economical from an exchange plant standpoint,

as the line capacity of the exchange is not reduced by the existence of lines 11 to 20 in the group, or by the retention of some of these auxiliary positions as spare for the future requirements of the PBX in question.

The private branch exchanges serving some of the large London stores have 150 exchange lines or more, but it is generally possible to divide the lines so that a group not exceeding 100 is available for outgoing traffic at the public exchange. In such cases additional switches of the pre-selector type are connected to the normal outlets of special third numerical selectors which act as final switches. The 10 outlets of the level appropriated to the PBX in question on each switch are multipled on a graded basis to "homing" pre-selectors having access to all the PBX lines in a common group of approximately 50 or 100, according to requirements. Each pre-selector is associated with a set of repeater equipment which provides facilities for battery feed, busy test, ringing and registration.

In this way all the requirements of very large private branch exchanges can be met in a perfectly satisfactory way, although with a certain sacrifice of uniformity as compared with systems deliberately designed for searching over large groups of lines.

(11) The Subscriber's Automatic Telephone Set.

The earliest Post Office automatic exchange areas were equipped with subscribers' apparatus supplied by the contractor whose exchange system was in use in each particular area. This led to the introduction of various types of instrument circuits and calling dials developed to suit the characteristics of the various systems. The first circuit employed was that of the Automatic Electric Co. in which the talking current from the exchange circulated directly through the transmitter and receiver in simple series; the receiver was of the electromagnetic type, i.e. it had no permanent magnet but was magnetized by the exchange current. This is an admirably simple circuit, but investigation showed its grade of speech transmission to be somewhat inferior to that of the standard common-battery circuit, which was utilized in connection with the automatic systems supplied by the Western Electric Co. and Messrs. Siemens Brothers. Another consideration in favour of the latter is that its adoption greatly facilitates conversion of standard common-battery manual exchange telephones to automatic working. When the question of standardization of subscribers' automatic telephones arose, the electromagnetic system was therefore discarded and the standard common-battery telephone circuit was adhered to.

Standard impulse.—After consultation with the contractors responsible for the principal systems, a standard impulse suitable for all types of exchange equipment was agreed upon. This was defined as a "break" period followed by a "make" period in the ratio of 2 : 1, i.e. the break occupies two-thirds of the total impulse period. In practice, dials are accepted if the "break" period comes within a range of 63 per cent to 70 per cent of the total. The standard rate of delivery of impulses is fixed at 10 impulse periods per second. All subscribers' dials are carefully maintained to function at this speed, but in order to reduce dialling time and to speed up operating, the dials used by operators on manual switchboards are specially adjusted to deliver impulses at the rate of 10·5 to 12 per second. The impulsing mechanism is only in operation during the return journey of the finger-hole disc after its release by the finger, so that the rate of impulsing is independent of any human factor.

Standard dial.—Following on the standardization of the impulse the provision of a standard dial for universal use was taken in hand and developed after consultation with all the Post Office exchange contractors. The dial produced as a result of these efforts embodied novel mechanical details designed by Messrs. Siemens Brothers, and is illustrated in Fig. 25.* At the rear of the dial a circular disc with 10 recessed gaps rotates in unison with the front finger plate. A spring, riding on the periphery of this disc, actuates a pair of contact springs which break and make a normally closed circuit as the spring rides in and out of the gaps when the disc rotates. These are the impulsing springs proper and it might

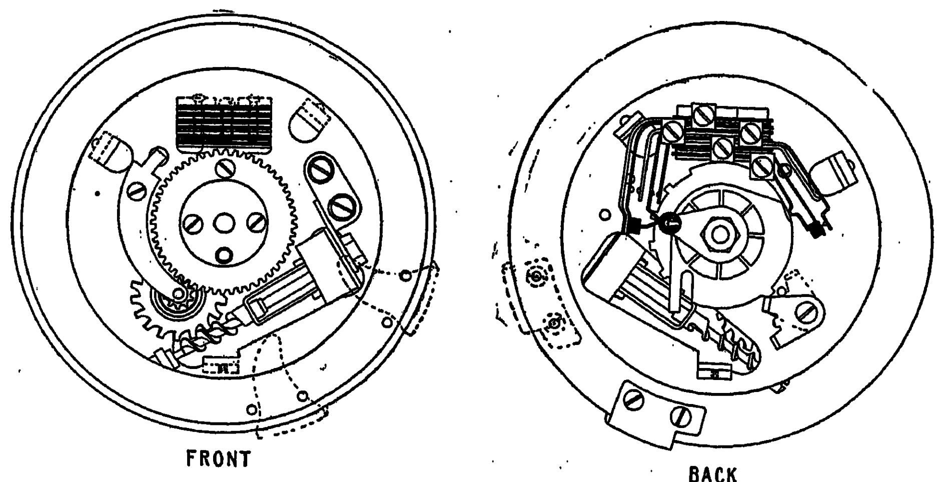

Fig. 25.—P.O. standard automatic dial.

* Photographs forming part of Fig. 25 are not reproduced in the *Journal*.

here be noted that this device, which secures the springs being pushed into contact for the "make" portion of the impulse and allows them to fall apart for the "break," eliminates "contact bounce" and gives a much cleaner impulse than the earlier device in which two contact springs normally held together by their own resilience were forced apart to give the break portion of the impulse, and allowed to fall together for the make portion.

During the forward rotation of the dial the riding spring is prevented from falling into the gaps in the circular disc by means of a friction sliding-cover plate, so that the impulsing springs are unaffected. The gaps in the disc are so spaced that they do not come into action until a certain portion of the return journey has been traversed. This provides an interval between the receipt of successive trains of impulses which gives the switching mechanism at the exchange ample time to perform its "trunk-hunting" operation after each train. Systems in which the call is first stored at the exchange on quick-acting registers, and subsequently released through the mechanism, do not require this hunting interval, and provision is therefore made on the dial for placing the finger-stop in an alternative position which reduces the length of pull for each digit and so speeds up the action of the dial.

In addition to the impulsing springs the dial also includes a set of auxiliary contact springs which make certain desired local changes in the circuit of the telephone while the dial is being operated. These springs are held in their normal position by an insulated stud attached to the circular disc. They assume the "operated" position as soon as the rotation of the disc begins, and maintain it until the disc has again come to rest in its normal position. The speed at which a dial returns to normal under the influence of its restoring spring, and consequently the rate at which its impulses are delivered, is "governed" by means of a geared centrifugal friction break whose retarding effect increases proportionately with its speed.

Complete instrument circuit.—The inclusion of the dial in the circuit of a subscriber's telephone can be effected in several ways, and the selection of the most suitable circuit arrangement has been by no means easy. The operation of the dial effects a rapid succession of interruptions in a circuit which includes exchange relays having considerable inductance. In the absence of special precautions these interruptions are accompanied by inductive surges or "kicks" which may run up to peaks of 500 or 600 volts and impose destructive strain on the insulation of instrument or exchange circuit wiring.

Other possible troubles arise from the alternate charging and discharging of the condenser in the bell circuit, which will cause the bell to tinkle in response to each train of impulses, and from the series of disconcerting clicks which may be heard in a subscriber's receiver while the impulses are passing.

The high dialling voltage can be materially reduced if the wiring be so arranged as to connect the condenser of the telephone across the break contacts of the dial during its operation.

The irregular tinkling of bells is always a nuisance and becomes a serious defect in the working of extension circuits, since the tinkling of the main station bell, when an extension station dials a number, is liable to be mistaken for an ordinary ring. For this reason it has hitherto been necessary to "bias" all bells used on automatic telephone sets, in the endeavour to obtain adequate security against tinkling under all conditions. The bell is "biased" by fixing an adjustable spring to the armature in such a way as to hold it normally over to one side, with the bell hammer resting against one gong. This gong must be the one which the hammer would strike when responding to tinkling impulses, in order that the impulses—which are always in the same direction—will have no audible effect on the bell. The addition of the "bias" spring not only represents an additional item of expense, in regard both to first cost and maintenance cost, but materially reduces the reliability of the bell. Any accidental reversal of the line connections renders it ineffective, and this remedy for tinkling can only be regarded as the lesser of two evils. The latest circuit arrangement overcomes the need for biasing and is greatly to be preferred.

Clicks in subscribers' receivers are obviated in all modern circuits by arranging for the auxiliary contact springs on the dial to short-circuit or disconnect the receiver during the operation of dialling.

Fig. 26 shows several circuits which have already been employed in order to reduce the undesirable local effects of dialling, and illustrates the successive stages in the development of the present standard circuit, in which they are all successfully overcome. It will be remembered that dialling takes place when the receiver is off the hook.

"A" shows the Automatic Electric Co.'s original circuit employing the electromagnetic receiver without induction coil. The bell is cut out of circuit during the process of dialling, and is therefore not subject to tinkling in so far as the action of its own dial is concerned. If, however, more than two telephones are connected to the same line, the main station bell is subject to tinkling when an extension station dials. No attempt is made in this circuit to suppress the high inductive dialling "kick," and high-grade insulation is therefore needed in all wiring. The auxiliary springs on the dial automatically short-circuit the transmitter and receiver during the period the dial is in motion, so that no clicks are heard.

"B" shows the earliest circuit of the Western Electric Co. which was applied to a standard common-battery instrument with induction coil and utilized a dial without auxiliary springs. It affords standard transmission, dials through the transmitter, and allows the subscriber to hear loud dialling clicks in the receiver. The dial is placed in series with the line circuit. The condenser is alternately charged and discharged as the dial springs make and break, but the presence of the induction coil and transmitter and receiver in bridge across the condenser reduces the magnitude of the charge and provides a discharge path clear of the bell, which is consequently immune from tinkling. It also involves the use of a 4-conductor cord between the table telephone and the bell box, in place of the standard 3-conductor cord.

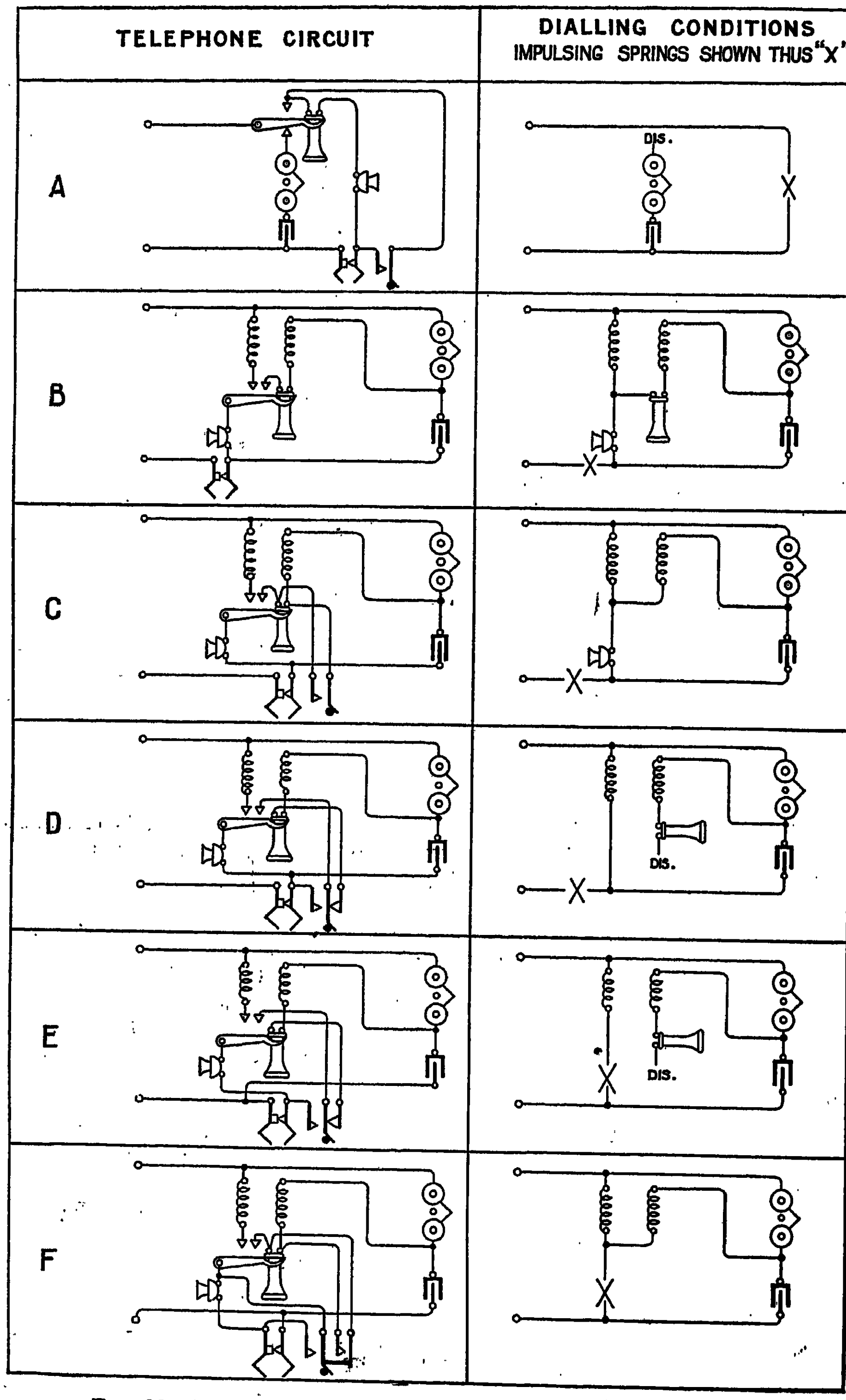

FIG. 26.—Development of subscribers' automatic telephone circuit.

"C" shows a more recent circuit provided for the Post Office by the Western Electric Co. It is identical with the circuit shown in "B" but includes two auxiliary springs, which short-circuit the receiver whilst dialling is in progress and prevent the subscriber from hearing dialling clicks. A 4-conductor cord is required.

"D" shows a circuit provided by Messrs. Siemens Brothers. It is very similar to that of "B" and "C," but the auxiliary springs short-circuit the transmitter and disconnect the receiver. The condenser is alternately charged and discharged as the dial springs make and break, but the magnitude of the charge is small because the condenser is charged through the high impedance of the 1 000-ohm bell and is shunted, at the moment of charge, by the primary (17-ohm) winding of the induction coil. The whole of the discharge current flows through the bell but is insufficient to cause tinkling. A 4-conductor cord is required.

"E" shows an arrangement which is used in some of the more recent installations in this country and is, I think, still the standard circuit of the American Telephone and Telegraph Co. Its chief advantage lies in the fact that it introduces a dial into the standard common-battery telephone without the need for more than three conductors in the cord to the desk set. The bell and condenser are connected permanently across the line, and the condenser serves to absorb high-voltage kicks during the dial operation, but its efficiency in that respect is reduced by the high impedance of the bell in series with it. The voltage across the condenser is alternately increased and decreased, as the dial springs break and make, and the bell is subjected to the full force of its charge and discharge. The bell therefore requires to be effectively biased in order to suppress tinkling.

"F" illustrates the arrangement and connections of the auxiliary contact springs in the new Post Office standard circuit—with 3-conductor cord. This circuit secures immunity from tinkling without resorting to biasing, and suppresses—or at any rate reduces to a negligible quantity—the high inductive dialling kick. When dialling is proceeding the condenser is bridged in series with the secondary 26-ohm winding of the induction coil across the "break" springs of the dial, in which position it momentarily prolongs the current after "break" and effectually prevents the high-voltage surge from the exchange apparatus from reaching a dangerous peak, while at the same time its action—as it is in series with only the low impedance of the induction-coil windings—is so rapid that no troublesome amount of impulse distortion is introduced. Immunity from tinkling is secured, as in the foregoing arrangement "C," by providing for the condenser to discharge mainly through the windings of the induction coil, which act as a shunt upon the bell. Dialling clicks are eliminated by short-circuiting the receiver. A separate pair of auxiliary contact springs is used to short-circuit the transmitter also, in order that constant dialling conditions may be maintained notwithstanding any alterations which it may in future be found desirable to make in the mean resistance of the standard transmitter.

The adoption of this very satisfactory instrument circuit was made possible by the fact that the new standard dial provides a robust and positive method of actuating the auxiliary contact springs. Springs which would short-circuit both the transmitter and receiver would undoubtedly have been employed several years ago but for the fact that one hesitated to attach to the earlier types of dial a spring set with more than one moving member. The spring set now used includes two separate moving members, and they are actuated in a manner which is, I think, safe and certain. Unfortunately this possible feature of the standard dial was not at once noticed, and those first obtained were fitted with spring sets of the then standard type, as shown at "E." It has, however, been possible to arrange that all on order for the London automatic service shall be converted to the new type in the course of their manufacture. The economy which will be effected in London alone, by obviating the need for fitting biased bells, is estimated to approach £100 000.

It will generally be admitted that the modern automatic calling dial is a remarkably simple little piece of

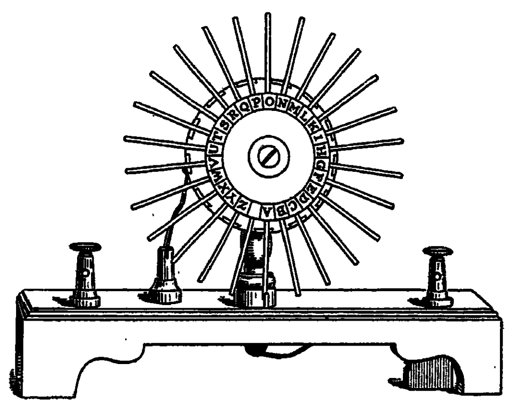

FIG. 27.—ABC dial sender.

apparatus, as compared with the immense complexity of the machine which it controls. This simplicity is the result of a long period of evolution since someone in the Automatic Electric Co. first had the happy thought of making a rotating disc with finger-holes for the purpose of sending the trains of impulses required for the Strowger automatic system. The master patent which secured a monopoly for this device ran from 1898 to 1912, and during that period a great deal of ingenuity was extended in inventing competing forms of dials and other signalling devices for other automatic systems which would not infringe the patent. It may be of interest to state that throughout this period an old and forgotten telegraph transmitting device was in existence which in all essential respects anticipated the terms of the master patent. This was one of the earliest forms, if not the earliest form of transmitter used in connection with the Wheatstone ABC telegraph system. A "clear-up" in one of the old store-rooms of the General Post Office in 1913 unearthed a specimen of this apparatus marked "Cooke and Wheatstone 1839" (see Fig. 27). It includes a disc provided with pivotally arranged finger-holds, which can be rotated from any position to a fixed finger-stop, for the purpose of trans-

mitting, by means of a current making-and-breaking device, a predetermined number of impulses of electric current, in harmony with the finger-holds—all of which terms represent the explicit claims of the master patent, so long considered unassailable. When it was discovered and brought to me as an interesting telegraph relic the patent had just expired.

(12) Tariffs for Automatic Systems.

The "message rate" tariff now in force in the British Post Office telephone service represents the only strictly equitable basis of general charge for such a service. It has the advantage of placing the small and large user on precisely the same footing, inasmuch as each will pay for his service in proportion to the broadly averaged overall cost of providing it and the use he makes of it. Under this method a fixed sum known as the installation rental is paid annually by the subscriber in respect of the plant provided for his individual use, and a uniform fee for each effective local call is collected to cover the cost of the plant provided for the common use of all subscribers, and the cost of operating. Additional charges are levied on a radial mileage basis for the use of long junction and trunk plant, affording connection with places outside the local fee area.

It is sometimes argued that the general introduction of the automatic system, and the elimination of the cost of operators to handle local calls, will bring in new conditions which would justify the restoration of the "flat rate," which connotes a uniform charge to all subscribers of a particular class, independent of the number of calls originated by each of them. This argument shows an entire misconception of the facts of the case. The introduction of the flat rate in connection with an automatic system would, of course, simplify the mechanical plant by making it unnecessary to provide metering arrangements for the registration of local calls, and would save a large part of the cost of collecting revenue from subscribers, but these points apply with at least equal force to the manual system, and in both cases they have to be subordinated to much more important considerations. In the automatic system, as in the manual system, part of the plant is provided for the individual equipment of each subscriber's line and part for the common service of all subscribers. The second part, which in all busy exchanges is much the larger of the two, depends entirely upon the amount of traffic to be carried; it has therefore no association with the annual installation rental, and a due proportion of its cost can only be properly charged against each subscriber in accordance with the traffic he originates. In a typical city manual exchange the ratio of individual to common service plant is about 1 to 2½; in an automatic exchange carrying equal traffic it is about 1 to 5. The actual cost per line of automatic plant in a busy city exchange is two or three times as much as in a suburban exchange forming part of the same system but having an average calling rate proportionately lower. At present only the local unit fee per message is registered electrically on the subscribers' meters in automatic exchanges, and all charges for calls beyond the local fee area are manually recorded on tickets by operators. It is, however, probable that in the near future it may be convenient to extend automatic metering to calls for which double or treble the unit fee is chargeable, and so enlarge the effective areas to which a purely automatic system of working can be applied. Schemes which provide, more or less satisfactorily, for such differential metering have already been devised, and the Post Office has been careful to keep the way open for future development in this direction by clearing all odd calculations out of its message tariff. All mileage fees are now so graded that the charge for any distance is an even multiple of the local unit fee, and could therefore be registered by adding a corresponding number of units to the record on the subscriber's meter.

One important respect in which the tariff considerations applying to the automatic and manual systems differ is that in the former the duration, or "holding time," of a call has a much more important effect upon the cost of providing the service.

In both systems switching and junction plant has to be provided on the basis of "traffic units," representing number of calls multiplied by holding time, but in the manual system the plant cost is rather overshadowed by the cost of operating the calls. The overall cost of providing service depends therefore to a much greater extent upon the number of calls than upon their duration, and no great error is made by assuming that all subscribers make calls of the same average duration. With the automatic system, on the other hand, the plant cost factor is of paramount importance. The various selecting switches through which a call passes may be looked upon as operators who have not only to make the connection in the first instance but are each required to give it their exclusive attention as long as it lasts. An exception to this is the "director" which will be used in London merely for the purpose of setting up calls, but the cost of directors is a very small fraction of that of the total traffic-handling plant.

It results, therefore, that the cost of providing service to any subscriber depends upon the aggregate duration of his calls in the busy hour, and not upon their number. One call of an hour's duration will cost the system practically as much as 60 consecutive calls of 1 minute. Under automatic conditions there is much to be said for the introduction of a method of charging for all telephone service on a time-and-distance basis, and the development of time-measuring methods applicable to local exchange working has received a good deal of attention from telephone engineers. Several patents already cover the application of this principle in such a manner that, immediately on the reply of the called subscriber, the meter of the originating subscriber will register one or more units in accordance with the distance between the parties, and repeat the registration at the end of each period of, say, 3 minutes. This does not fit in very well with the adoption of varying charges at different periods of the day and night, which is also a reasonable thing in telephony from the standpoint of keeping the plant occupied and revenue-earning outside the normally busy hours. A preferable system would appear to be to record normal time units by metering impulses at short intervals of, say, 12 seconds

throughout the period of connection, counting 10 or 12 units as the equivalent of a penny call. For calls to points outside the local area the record might be made at double, triple, or quadruple speed, by drawing impulses from different contact cams in the controlling clock. Reduced tariffs during normally slack periods could be introduced by variable driving gear which would slow down the whole impulse system in as many stages as might be desired.

(13) Progress of Automatic Exchange Construction.

The character of the new automatic exchanges to be catered for in London and the provinces in the immediate future is shown in Appendix 2. It will be observed that the schedule includes 161 projected exchanges with a capacity of about 369 000 subscribers' lines. Before this large amount of work can be completed many additional requirements will no doubt have matured. Extensions of existing provincial automatic exchanges will also be necessary in order to meet development.

The steps taken to provide for the special telephonic needs of London and to encourage British manufacturers to make plant of uniform characteristics have already been mentioned.

The difficult matter of acquiring sites, at or near the positions indicated by economic studies of the area layout, and designing and providing the necessary buildings, is proceeding as rapidly as present conditions allow. The contractors concerned in the manufacture of the exchange equipment are all working hard to produce and install the plant by the dates required, and their staffs of able engineers are in continuous touch with the Post Office Engineering Department. The Post Office staff responsible for planning and providing the external cable plant, and for grafting it economically into the London cable network, are also working strenuously under conditions rendered more and more difficult by the rapidly increasing congestion of underground London and the necessity for reducing street openings to the utmost possible extent. In some central districts it is no longer possible to find space for the necessary cable ducts under footways and roadways, and tunnelling deep down in the London clay has to be resorted to in order to gain adequate access to exchanges.

Automatic developments on so large a scale necessitate also the provision of a very highly skilled staff to engineer, supervise and maintain the exchanges. In order to meet this great need, it has been found desirable to set up a very completely equipped training school at the General Post Office for the purpose of giving a thorough training to the staff of the Engineering Department in the theory and practice of automatic telephony, and in the delicate work of switch adjustment, fault tracing and cognate matters. Graduated courses of instruction are held for the skilled workmen who will actually maintain the exchanges, as well as for inspectors and engineers who will be responsible for the performance of the mechanism and the efficiency of the service rendered. The extreme complexity of modern automatic circuits and equipment is illustrated by the the fact that a single automatic switching unit of 10 000 lines comprises no less than 5 000 000 " bank " contacts representing selectable outlets. Any one subscriber in such a unit can obtain connection with any other particular subscriber in the same unit via more than 240 000 different linkages. To reach all the subscribers on the unit he has at his disposal more than 2 400 000 000 different linkages—all this without passing outside his own exchange of 10 000 lines. In his recent book " Fifty Years of Electricity " Dr. Fleming expressed the opinion that the design of modern automatic telephone systems represented " the high water mark of human creative power." Be this as it may, it seems improbable that a parallel could be found, in any other application of science to industry, to the mass of co-ordinated and controlled complexity constituted by the automatic machine required to meet the telephonic needs of such cities as New York and London.

The manufacturing organization necessary for the production of the automatic equipment needed throughout the Empire, and in foreign markets which British manufacturers have been able to secure, is very vast and complex. It is anticipated that, in the near future, an annual output of automatic equipment for a quarter of a million exchange lines will be producible in the factories of this country.

From the first inception of the Post Office telephone system it has been the policy of the Department to discontinue the purchase of telephone plant from abroad and to encourage the establishment, within the United Kingdom, of adequate manufacturing resources for the supply of all its needs. It was well recognized from the first that this would foster the setting up of a British industry which would cater for a far more extensive market than that represented by Post Office requirements, and the complete success of this policy is a matter for lively satisfaction.

APPENDIX 1.

KEIGHLEY EXCHANGE.

COMPARATIVE STATEMENT SHOWING ESTIMATED COSTS UNDER MANUAL AND AUTOMATIC SYSTEMS.

(a) Busy-hour calling rate 1
(b) Proportion of local traffic .. .. 60 per cent
(c) Proportion of manual positions retained under automatic .. .. .. 60 per cent

	1925		1930		1935 (1 260 lines)	
	Manual	Automatic	Manual	Automatic	Manual	Automatic
Capital outlay—	£	£	£	£	£	£
Exchange equipment	7 490	13 854	8 803	16 562	10 095	18 717
Subscribers' apparatus	4 704	5 009	5 725	6 253	6 673	7 429
	12 194	18 863	14 528	22 815	16 768	26 146
Annual costs—						
Interest	671	1 037	799	1 255	922	1 438
Depreciation	636	718	760	876	878	1 013
Maintenance	1 303	1 405	1 456	1 547	1 744	1 849
Operating	2 053	1 545	2 294	1 564	2 595	1 764
Total annual costs	4 663	4 705	5 309	5 242	6 139	6 064
Balance of annual costs in favour of manual ..	42	—	—	—	—	—
Balance of annual costs in favour of automatic ..	—	—	—	67	—	75

Costs which are common to both manual and automatic systems have been omitted from this statement.

MAIDSTONE EXCHANGE.

COMPARATIVE STATEMENT SHOWING ESTIMATED COSTS UNDER MANUAL AND AUTOMATIC SYSTEMS.

(a) Busy-hour calling rate .. .. 0·7
(b) Proportion of local traffic .. .. 70 per cent
(c) Proportion of manual positions retained under automatic .. .. .. 28 per cent

	1926		1931		1936 (1 550 lines)	
	Manual	Automatic	Manual	Automatic	Manual	Automatic
Capital cost—	£	£	£	£	£	£
Exchange equipment	8 458	14 068	11 346	19 073	13 744	22 315
Subscribers' apparatus	4 388	4 944	6 449	7 210	8 340	9 288
	12 846	19 012	17 795	26 283	22 084	31 603
Annual costs—						
Interest	626	927	868	1 281	1 077	1 541
Depreciation	685	757	956	1 060	1 192	1 296
Maintenance	1 526	1 722	2 186	2 466	2 822	3 186
Operating	1 390	535	1 865	764	2 526	1 136
Total annual costs	4 227	3 941	5 875	5 571	7 617	7 159
Balance of annual costs in favour of automatic ..	—	286	—	304	—	458

Costs which are common to both manual and automatic systems have been omitted from this statement.

APPENDIX 1—*continued.*

MACCLESFIELD AND PRESTBURY EXCHANGES.

COMPARATIVE STATEMENT SHOWING ESTIMATED COSTS UNDER MANUAL AND AUTOMATIC SYSTEMS.

(*a*) Busy-hour calling rate .. .. 0·8
(*b*) Proportion of local traffic .. .. 75 per cent
(*c*) Proportion of manual positions retained under automatic .. .. .. 53 per cent

	1925		1930		1935 (875 lines)	
	Manual	Automatic	Manual	Automatic	Manual	Automatic
Capital outlay—	£	£	£	£	£	£
Exchange equipment	4 694	10 723	5 951	13 345	6 507	14 964
Subscribers' apparatus	3 261	3 433	4 472	4 890	5 248	5 822
	7 955	14 156	10 423	18 235	11 755	20 786
Annual costs—						
Interest	438	779	573	1 003	647	1 143
Depreciation	419	511	552	697	627	802
Maintenance	784	811	971	1 015	1 156	1 205
Operating	734	480	876	549	1 183	573
Total annual costs	2 375	2 581	2 972	3 264	3 613	3 723
Balance of annual costs in favour of manual ..	206	—	292	—	110	—

Against the balance in favour of manual working shown in the statement, there will be an annual saving of £220 on line plant by the use of automatic.

APPENDIX 2.

PROPOSED NEW AUTOMATIC EXCHANGES.

London		Provinces		
Name of exchange	Approximate number of lines	Name of area	Number of exchanges	Total number of lines
Beckenham	1 600	Bath	4	4 000
Bermondsey	2 000	Bedford	1	1 500
Bishopsgate	8 500	Birmingham	5	20 000
Central	10 000	Brighton	6	8 500
City	4 400	Bristol	5	8 000
Cricklewood	3 000	Burnley	1	1 700
Croydon	3 800	Chatham	4	2 000
Edgware	1 000	Cheltenham	2	1 400
Fulham	4 000	Chesterfield	2	1 100
Guildhall	10 000	Colchester	1	1 000
Hampstead	3 800	Colwyn Bay	2	3 000
Hendon	1 500	Coventry	2	3 500
Holborn	10 000	Dudley	4	3 000
Holloway	2 000	Edinburgh	4	15 600
Ilford	2 500	Exeter	2	2 000
Kensington	6 000	Folkestone	4	2 000
Kentish Town	2 700	Gloucester	1	1 200
King's Cross	3 000	Halifax	1	3 200
Langham	9 100	Hanley	7	4 300
Maida Vale	6 000	Harrogate	1	2 600
Monument	6 700	Hereford	1	1 000
Oval	2 000	Ipswich	1	1 300
Primrose Hill	4 700	Keighley	2	2 000
Sloane	8 700	Kirkaldy	1	800
Strand	7 400	Leeds	4	4 000
Tandem	—	Leicester	4	9 300
Thornton Heath	1 000	Liverpool	1	10 000
Wandsworth	3 000	Macclesfield	2	2 000
Western	8 100	Manchester	5	20 000
Whitehall	10 000	Newcastle	5	12 000
Wood Street	10 000	Nottingham	4	11 000
Woodside Park	2 000	Oxford	1	1 400
		Plymouth	2	4 000
		Portsmouth	1	600
		Rochdale	8	3 700
		Sheffield	9	13 300
		Shrewsbury	1	1 000
		Southend	3	4 000
		Southport	4	7 100
		Torquay	2	1 800
		Wakefield	2	2 000
		Walsall	2	2 000
		Watford	1	2 000
		West Hartlepool	2	1 400
		Wolverhampton	2	3 000
32 exchanges	158 500 lines	45 areas	129 exchanges	210 300 lines

Discussion before The Institution, 5 March, 1925.

Mr. E. A. Laidlaw: The present paper is a record of the very striking progress made since 1919, when Mr. Grinsted and I read our paper on the same subject. Our paper was an attempt to deal with the future: the present paper is an account of the past—it describes what the Post Office has decided and done. For this reason it is difficult to discuss in a constructive manner. It would be easy to criticize the decisions and methods adopted, but such criticism would be merely destructive and I wish to avoid that. It is a very great satisfaction to confirm the author's remarks in the last paragraph of the paper as to the complete success of the Post Office policy of drawing upon British resources for the supply of all its needs. This policy has been of the greatest possible assistance to firms like my own, and we recognize it gratefully. I trust that it will continue to be the policy of the Post Office to depend upon the British manufacturer and, perhaps, to an even greater degree than in the past, upon British engineering. If that is done the author may relieve himself entirely of the fear he expresses in Section (9) of the paper. He may then rest assured that the London system in 20 years' time *will* be a model for the world to copy. The system of grading the links between ranks of switches which he describes in Section (5) is entirely British practice, and the standard dial described in Section (11) is a purely British product. It is, I believe, the only dial to have had thorough scientific study applied to its development, which took three years in our experimental departments. It is operating with great success in Australia, Canada, India, Japan, South Africa and South America, and we have even sold a quantity to a company associated with the American Bell interests. I was pleased to note that the A.T. and T. Co.'s * instrument circuit has been superseded by a very much better circuit developed, I believe, by the author's staff. The author referred to the paper by Mr. Grinsted and myself. I should like him to remember that it was read six years ago immediately after the war finished, and written before that, and that its main purpose was to draw attention to the changes in conditions which had taken place and to discuss the technical and economical problems then confronting telephone engineers. We used London merely as an example, in which we were expected to find specimens of every difficulty likely to be met in the application of mechanical operation. We did not intend to attempt to solve the London automatic problem, and this is clearly stated in the paper. We pointed out that the manual system was incapable of fulfilling future requirements, and held up the full automatic system as the solution of the difficulty. We condemned the semi-automatic system. I believe this was about the time to which the author refers, when the Post Office was seriously considering its adoption. In these respects events have justified our opinion. We also, it is interesting to note, fully described a scheme for "telephone unit" metering, arranged to charge the subscriber on the basis of the time and amount of plant occupied on his call. It appears from the author's remarks in Section (12) that he agrees with us as to the correctness and desirability of such a system. Here, again, I am confident that our opinions will be justified by events. Has the author had any investigation made as to what extent the telephone user can be depended upon to listen for the "dialling tone"? Observations which I have made, both at home and abroad, show that practically no one listens to it. A prominent official of one of the telephone companies of the United States using the panel system informed me that they had made an investigation and watched 200 subscribers carefully without their knowledge, and not one listened in for the tone before dialling. The effect of this on the working of the system will undoubtedly be felt, not at the beginning but when the load rises to the figure for which the exchange is designed. I think that it will be extremely difficult to educate subscribers to obey an instruction which they can ignore without trouble on about 95 per cent of their calls.

* American Telephone and Telegraph Co.

Mr. G. H. Nash: In Section (9) of the paper the author states: "Exhaustive study and trial led to the conclusion that the director system contained all the essentials required as a basis on which to frame a complete equipment of circuits and apparatus admirably fitted for the service of such an area as London." Complete as this paper is, in so far as it is possible for such an immense subject to be reviewed in a single paper, I do not feel that the author has done justice either to himself or to that able body of men who report to him and I make no apology for endeavouring to give some idea of what it is these men have done. It is apparent from the quotation I have just given that when the Post Office engineers decided to turn from that wonderfully complete system designed for the New York area—to leave behind the comfort and advantages to be derived from not being pioneers, and to become pioneers—they showed a great degree of courage and resourcefulness. It is well known that the commercial prosperity of a city and of a country is very closely related to its telephone development, and it requires no great stretch of imagination on our part to appreciate what would happen to London, for example, if the telephone service were to break down or become highly inefficient. Following this line of thought, it is apparent that the Engineer-in-Chief and his assistants embody in their persons a great responsibility for the commercial success of this city and of this country. Therefore, when they decided to take a system which, in its then embryonic stage, provided nothing greater than—to use the author's words—"a basis on which to frame a system for London," they demanded a most unusual amount of courage and resourcefulness from themselves and from the other telephone engineers of this country. It requires a telephone engineer to appreciate what a vast thing a telephone system is, but it is given to very few to get a complete view of what does lie behind such a system. I should like to lift one small corner of the manufacturing veil, taking as an example one of the manufacturing firms who are designing and will manufacture the system

for the Post Office. Taking circuits alone, there are something like 90 circuits in the director system which have to be built up and studied individually and collectively. In this one firm of which I speak, we have had 17 men for over a year doing the actual paper design work on those circuits alone—simply as theoretical paper circuits. Another 20 have been continually engaged in setting them up, testing them, finding out their faults and then dismantling them. Other men are engaged in designing the apparatus and in life-testing it before its construction can be proceeded with. I have not said this to call attention to a particular firm,

TABLE A.

Traffic units	Number of secondaries required Loss = 0·001	Number of outgoing trunks required		Saving effected by secondaries (trunks)
		(1) With secondaries. Loss = 0·001, overall loss being 0·002	(2) By practical grading. O'Dell's formula for loss = 0·002	
15	39	29	36	7
20	65	37	47	10
25	82	46	59	13
30	98	54	70	16
35	114	61	81	20
40	131	69	92	23
50	163	84	114	30
60	196	98	137	39
70	228	111	159	48
80	261	125	182	57
90	291	139	204	65
100	326	152	226	74
110	359	166	249	83
120	391	180	271	91
130	424	193	294	101
140	457	206	316	110
150	489	219	338	119
160	522	231	361	130
170	554	244	383	139
175	570	250	395	145

but to demonstrate the amount of work which has to be done. I have heard doubts expressed as to whether the director system for London will be a success and whether the Post Office has been wise. My opinion is that without doubt it will be a complete success. Turning now from this broad review to a matter of detail, the author states that the Post Office has adopted the grading principle for trunking, which means that on any group of trunks from one exchange to another the trunks run straight from a digit-selecting switch in the outgoing exchange to the incoming switch. The actual process of grading allows access of a few switches to the trunks connected to the earlier choices, and the number of switches on the trunks connected to the later choices to be gradually increased. A certain gain in efficiency is arrived at by this means. This problem of trunking efficiency is of interest the world over. There are two particular areas at the moment which, like the Post Office, are confined to using switches with only 10 outlets, where it is of vital importance to know what to do to increase trunking efficiency. The question arises as to whether grading or, alternatively, outgoing secondary switches, shall be used. It will be realized that if there are switches with a large number of outlets the problem does not arise; neither would it arise if one could use pre-selecting outgoing secondary switches, i.e. switches which themselves found the line before it was wanted. All the attempts which have been made to design suitable controlling circuits for pre-selecting outgoing secondary switches have not yet produced a result which really warrants their being included in any automatic system. Such a circuit will no doubt arrive and, when it does, outgoing secondary switches of a pre-selective type will for 10-point switches (I do not refer to other types) completely sweep the board. As things are at present, we have to consider post-selecting secondary switches, and it will be seen from Table A that in order to pass a certain number of traffic units the grading principle may be employed, as the Post Office does, or post-selecting outgoing switches may be used. If outgoing switches are used they have to be paid for, while if the grading system is used more trunks will be needed. The London choice is for grading.

Considering Table A and taking, for instance, traffic units (35) the number of secondaries required on a loss of 1 in 1 000 is given, and it will be seen that an extra 114 switches have to be purchased, with all their attendant apparatus. In col. 3 is given the number of outgoing trunks that would be required, while in col. 4 the number of trunks required with the grading principle is shown to be 81, the difference being 20. The question therefore resolves itself into whether money is to be sunk in 114 secondary switches or in 20 trunks.

Mr. F. Morley Ward: The author seems to have covered the ground so thoroughly and so ably that it is difficult to find any matter for criticism. It is very interesting to see the "grading" diagram described in the paper and to know that the opinion of Post Office engineers as to the saving effected by such a scheme fully confirms my own contention. I believe that this arrangement was originally due to Mr. W. Aitken, who named it "multi-choice" grading. It was adopted by the Relay Co. over nine years ago and has proved a very useful and economical arrangement even for very small groups. It would be interesting to know the reasons which caused the Post Office to make the nine decisions referred to in the paper. Some of these seem quite obvious to British telephone engineers, but others are not so obvious. It would be particularly interesting to know why impulses over junction circuits should be signalled round the loop and not over one earthed conductor, especially when the latter permits of dialling over much longer lines. I believe that Messrs. Siemens have employed dialling over one line and the Relay Co. have gone further and dialled over both lines in parallel. By dialling over the two lines in parallel it has been found possible to work over junction circuits up to 1 600 ohms loop resistance, employing only 32 volts, which, I imagine, must be con-

siderably more than can be done on the Strowger system employing 50 volts. The reversed-battery arrangement which the Post Office has decided to use for signalling over junctions seems to me to be less flexible than the scheme which the Post Office standardized for manual junction working, in which signalling is made in one direction over one line and in the other direction over the other line. The latter scheme has been adopted very successfully by some automatic telephone companies. Perhaps the author will furnish some information on these points.

Mr. W. R. Carter: The author has told us how, during the time that negotiations were proceeding for the introduction of the panel system into London, those interested in other systems were not asleep, and it will probably interest members to learn that prior to the development of the director, the adoption of which is naturally a source of keen gratification to my company, our engineers had devised another method directed to solving the problem of the telephoning of large cities and by which it was possible to retain existing exchange names as part of the numbering scheme without, however, using translation. This method used what has been termed a "universal switcher," a device built up of standard Strowger equipment, and embodying an elaboration of the switching selector repeater principle. Fundamentally, the plan used was to seize a number of junctions, any one of which might prove to be the one wanted, and to reject those not required. That is, if BAR were dialled for Barnet, junctions would be seized momentarily, in addition to others going, say, to Bank and Battersea, or to switching centres having junctions to those places, and these junctions would be released as the dialling proceeded. The weakness of this scheme was, of course, the wasteful use of the junction circuits, but its development will indicate that considerable effort was being directed to finding a solution of the problem. Referring to the reasons given by the author for the adoption of the Strowger director system, I do not think that it is possible to overestimate the advantage of being able to use the same switching mechanisms in a 50-line village exchange as in the mechanical tandem exchange or in any 10 000-line office, and of being able to use any member of the maintenance staff who is capable of maintaining the 50-line exchange without further training in the larger offices. This must constitute a valuable advantage to those responsible for the maintenance of the system. Then, again, the system which has been adopted, whilst maintaining the ideal of one form of switching mechanism throughout, only employs registers and translators in those areas where it is necessary or desirable to separate the trunking and numbering systems. Maintenance considerations also controlled the design of the coder call indicator. The substitution of code impulses for decimal impulses makes it possible to use simple rotary switches and relays only at the manual end and, in addition, reduces the amount of equipment at that end to a minimum, an important feature since there is often but little space available for additional apparatus in existing offices. Post Office practice largely influences the development of the art; innovations suggested by Post Office engineers have become standard, and may be found in service in many parts of the world. In this connection the work of the Post Office engineers in investigating grading methods of interconnecting is likely to prove particularly valuable to the industry at large.

Mr. W. Aitken: The idea of telephoning great areas has always had a fascination for telephone engineers. Prior to 1900, Mr. A. R. Bennett put forward a system having this object in view. In 1903 I read before the Institution a paper * advocating a manual system of three divisions whereby the subscriber, in addition to lifting his receiver, by pressing one or other of three keys could get into any one of three great divisions. In 1914 I advocated, or at least designed, a system (British Patent No. 53) for the tandem working of junctions, a system which is a valuable feature in the present director system. In that case I associated an electro-mechanical coding sender with the jack of each outgoing junction line. In 1919 we had the paper by Laidlaw and Grinsted, who put forward their ideas for automatic development, in which connection I also read a paper in 1911 chiefly on the Strowger system.† Now we have this system, in its director form, put forward and actually being installed by the author, a system which, in my opinion, represents one of the most wonderful creations and designs of the human mind ever known. It is marvellous in its adaptability to the business and social needs of a great community. It is almost confounding in the intricacy and efficiency of its circuits, and it is awe-inspiring in the more than human exactness, discrimination, reliability and durability of its switches. The system of grading trunks from a small group to a large group—first and second choice—was known, at least, in 1910 and was described in Smith and Campbell's "Automatic Telephony" in 1914. Siemens and Halske in 1913 (British Patent No. 12566) divided at one or more places the multiple leads connecting the several parts of the divided leads to different lines of the group, the contacts of the divided leads being preferably the first engaged. In 1914 (British Patent No. 20453) I applied this to manual and semi-automatic systems, with direct trunks, without order wires, an operator pressing a key to glow a group of multiple engage lamps, and first using an idle trunk in the first-choice sub-group until these were all busy, and then taking up second-choice trunks. This was submitted to the Post Office but was withdrawn at a later date. In 1915 I developed a multi-choice arrangement (British Patent No. 15287) on the lines put forward by the author. Unfortunately for the originality of my idea (it was original in this country and in many others, according to the Patent Offices) there was an American patent on the subject and it seemed that what I had put forward had been advocated in America. Like the British patent, however, the American patent had been ignored until rediscovered or invented by the Post Office engineers. The graded wiring of trunks is now put forward as the most valuable contribution towards increasing the efficiency of small switches and making their efficiency approximately equal to that of switches of great capacity. In 1916 I designed

* *Journal I.E.E.*, 1903, vol. 32, p. 705.
† *Ibid.*, 1911, vol. 47, p. 651.

"multiple graded access" (British Patent No. 108714) in which a diminishing number of trunks in each access were multipled a plurality of times over a large group of incoming lines (one or more thousands), the number of trunks in each access having, preferably, no common divisor, such as 19, 17, 13, 11, 7, 5 and so on; 19 trunks, for example, would be multipled over each sub-group of 19 lines in the group, as first choice; 17 trunks over each 17 lines, as second choice, and so on; so that adjacent incoming lines had access to a different set of trunks. My object was to find a means of making systems with small switching access, say to 5 or 6 trunks, efficient, and tests showed that that object was very well attained.

Mr. J. E. Collyer: The automatic telephone programme will give great satisfaction to everyone, and particularly is this the case with regard to London. When one learns from the paper the history of the development, one can appreciate the magnitude of the difficulties encountered and the importance of the decisions that had to be made. When a course is chosen from several alternatives there are bound to be doubts and disappointments. After reviewing the matter carefully in the light of the paper, I think that the Post Office has acted wisely. Speaking as a representative of the engineering staff of the General Electric Co., we are determined to give the Post Office all the assistance in our power in carrying out its programme. The author suggests that such standardization as is taking place has nothing to do with any idea of finality or fixation of practice. One has only to turn to other instances to realize the advantages of standardization. At the same time I feel—in common, I think, with many other engineers—that this matter should be dealt with very carefully and diplomatically at this stage, as otherwise there is a great danger of standardization affecting progress. The fact that something is considered good enough for the time being must not result in the cessation of further effort. In the opinion of many engineers there will be very considerable changes during the next few years.

Mr. G. Deakin: The author sets forth clearly the difficulties encountered by engineers when attempting to solve the telephone problem for very large networks, and his final selection of a system of translation for London is an appreciation of the economies which translation affords. At some later date it will be interesting to compare the results obtained in London with those obtained in Berlin where translation will be avoided. Office-prefix translation is now in use in many cities in America and in one city in Europe, namely, Copenhagen. The idea of spelling the office prefix by placing letters on the dial was conceived by Mr. W. G. Blauvelt of the A.T. and T. Co. The first flexible translating register circuit was produced by Mr. A. E. Lundell, then of the Western Electric Co. of New York. The Copenhagen circuits were developed by Mr. L. Polinkowsky, of Antwerp. It is stated in the paper that a satisfactory amount of traffic can be carried with 10 contacts in a bank-level. Presumably this means that the author is satisfied that such an arrangement is economical, both as regards the inside and outside plant. I have made studies of two Continental cities and in each case found that a real saving could be made by employing larger junction groups. In these studies the junctions were calculated for three conditions as follows: (*a*) undivided groups; (*b*) groups of 30 which are now obtainable in the rotary system of the Western Electric Co.; and (*c*) groups of 10. The average results were as follows: Plan (*b*) required 23 per cent more circuits than plan (*a*); plan (*c*) required 69 per cent more circuits than plan (*a*); while plan (*c*) required 38 per cent more circuits than plan (*b*). These figures are not negligible, but the real answer has more to do with the length and character of the junctions involved. Where the junction routes are short, underground and in cables of many conductors, the annual cost of the excess junctions may not be great, but where the junction routes are long and important the result would seem to be the reverse. I do not dispute the accuracy of the author's statement as regards London, but it comes as a surprise to me. Tandem trunking is one of the economical features of an automatic system, and I presume that the statement with regard to the efficiency of a group of 10 junctions does not apply to all points on tandem routes. The reason for tandem trunking is, as the author states, to increase the efficiency of long and expensive junctions, and one of the ways of doing this is to increase the size of the junction group. Grading will, of course, help, but grading applies to both large and small groups. The paper brings out very clearly the advantages of grading which is now universally recognized as both economical and proper. The real efficiency of any particular form of grading is, however, at the present moment open to dispute, since it seems to be impossible to demonstrate mathematically, to the satisfaction of all, within practical time-limits the efficiency of such schemes as that shown in Fig. 12, which is but one of a very large number of similar schemes that may be applied to the various stages of selection. Furthermore, in trunking from the group selectors, i.e. from the first, second, etc., selectors, the scheme of grading must be very general and capable of immediate application from day to day when increases or decreases in equipment are being made. In planning any scheme of grading the abnormal conditions actually met with must be taken into consideration. This is particularly important in grading small groups, for the reason that a few calls of abnormal duration unfortunately placed may seriously affect quite a large number of switches. The author mentions that cordless "B" positions will be used to establish connections outgoing from the existing manual exchanges to the new automatic exchanges, and gives, as the alternative, dials placed on the "A" positions by means of which the "A" operators may dial direct. This method of direct trunking is obviously not economical, but there are methods of direct trunking which are. I refer particularly to key-set direct trunking from "A" positions over individual junction jacks. This scheme of trunking is made economically possible by the use of large-capacity high-speed power-driven finders. Each "A" operator is provided with 2, 3, 4 or 5 individual jacks, as traffic requires, for connection to each automatic office. On each "A" position is mounted a small 10-button key-set approximately $2\frac{1}{4}$ in. × $3\frac{1}{4}$ in. This key-set is held by clips so that no cutting of the existing keyboards is

necessary. The direct trunking equipment has no connection whatsoever with the "A" cord circuits or with the operator's telephone circuits, so that the existing manual equipment need not be disturbed in any way. The method of operation is as follows: The manual subscriber gives the "A" operator the wanted number, for example, Gerrard 1456. The operator upon hearing the prefix immediately inserts the calling plug into an idle junction jack to the Gerrard office, no busy test being necessary. As soon as the number has been checked with the subscriber the operator depresses the wanted number on the key-set one digit at the time, each time depressing the proper button all the way down. The four buttons may be depressed one after the other, providing the operator is able to do so, within $\frac{3}{8}$ sec. without failure. The operator finishes with the setting-up of the call with the depression of the last button. From now on, the call takes care of itself. The great advantage of this sort of direct trunking over order-wire trunking is that the "A" operator's load may be increased while "B" operators are dispensed with. Direct trunking with key-sets is not new and has been in satisfactory operation in America, in connection with the panel system, for some time. In America, however, multiple outjunction jacks are still used so that an "A" operator must select the junction and connect it to her key-set, and this she does by depressing an office key, similar to an order-wire key, which causes the number of the assigned junction to be displayed before her. This extra operation constitutes quite a little work over and above that required under the afore-mentioned individual jack scheme, but even with the American scheme the relative weight of a trunked call has been brought down from 1·5, which is the well-known order-wire figure, to 1·21. It is confidently expected that the individual jack scheme which will be put into operation in Switzerland early next year will reduce the weight of a trunked call to that of a call completed directly in an "A" multiple. The factors which tend to decrease or simplify the work thrown upon the "A" operator may be briefly stated as follows: (1) No repeating or checking with another operator; (2) elimination of order-wire key or its equivalent, and the associated delay; (3) individual junction jacks reducing time of jack selection; (4) no busy or check testing of junction jack; (5) very short reach, which incidentally reduces cord congestion; (6) no team work required or divided responsibility; (7) operator may plug into junction jack as soon as wanted prefix is heard and before or while the number is being checked with the subscriber; (8) number may be depressed on key-set as fast as the operator can work, and in the most simple manner. Studies have been made to determine what saving might reasonably be expected from direct trunking when applied to manual offices. In one study a network of eighteen 10 000-line offices was considered, nine automatic and nine manual. Each manual office was assumed to complete 10 per cent of the originating calls locally in a subscriber's multiple, to trunk 45 per cent to other manual offices over order-wire junctions and the remaining 45 per cent to automatic offices. In comparison with cordless "B" trunking, the study showed that direct trunking saved fifteen "A" and eighteen "B" positions for each manual exchange of 10 000 lines. The study also showed that the cost of the direct trunking equipment was not much greater than that of the cordless "B" equipment plus the excess "A" position equipment made necessary by the use of cordless "B" positions. In this particular study the net annual saving for each manual office of 10 000 lines was estimated to be 600 000 francs (French). This saving will increase in proportion to the growth of trunking to automatic. Incidentally the capacity of manual switchboards increases with the growth of the automatic system, so that additional subscribers may be added to existing manual exchanges without extending the sections. Direct trunking improves service during the transition period. Order-wire trunking has never been an ideal form of trunking and never will be. It has rarely been successful on the Continent, and in many important instances has been a dismal failure. On the Continent to-day, in large manual networks, there are many methods of trunking other than order-wire in actual use. Even in America, where order-wire working has been very successful, a new scheme of trunking called "straight-forward trunking" has come into vogue. Under this scheme an order wire is not used. I am not able to give any details, but it would seem from the information so far received that the trial installations are very successful. An order wire requires the best possible team work between two operators, and even with the best team work the possibility for misunderstanding is always there. The order-wire method of trunking is a constant source of wrong numbers, double connections and "hang-ups." Furthermore, the order wire at moments of overload and even at other times may be a serious source of delay to the "A" operator, resulting in slower and less satisfactory service and in lower operating loads and more costly operation at the "A" end. When all these points are fully considered, direct trunking under proper conditions appears very attractive.

Mr. W. H. Grinsted: The author has, at more than one point in his paper, drawn attention to the complexity of the apparatus. It is very important to see how this complexity tends to affect the reliability of the system. A connection in an automatic system is made up, like a chain, of a large number of links, and the success or failure of the connection depends entirely upon the reliability of the individual links. The failure of any one link will interfere with the completion of the connection. I am not sure whether it is generally realized what a very large number of links is involved. I am using the word "links" to include not merely the trunks connecting successive ranks of switches but also the separate movements or functions of each piece of apparatus. Taking the London system as an example, and choosing a call between two adjacent exchanges, the number of individual movements of different pieces of apparatus —movements the failure of which would interfere with the success of the connection—amounts to 565 for one call. If we count the number of circuit openings and closures and regard each time a circuit opens or closes as a function, the number amounts to 1 539. Taking the average provincial system, the figures are 169 (reckoning movements alone) and 600 (taking into

account circuit-changes). Carrying this idea a little further, the importance of each piece of apparatus from the maintenance point of view depends both on the number of functions it performs—its complexity in a way—and the amount of traffic passing through it, i.e. the number of times it is asked to function. Taking the director system and calling the traffic carried by a line switch unity, that carried by a selector, on the average, might be represented by 10 and by a director by about 50. Not only is the traffic concentrated on the director to that extent, but the director performs a far greater number of functions. Out of the 565 movements to which I have referred, the director accounts for 234. If, then, we compare the different parts of the equipment on the basis both of complexity (number of functions and movements) and traffic (the number of times it is asked to function) we might represent the importance of the line switch and its associated apparatus by about 10 movements multiplied by 1, whereas in the director the corresponding figure will be about 234 multiplied by 50. That shows how very important the directors are and how large a share of the attention of the maintenance staff they are likely to occupy. Another point which I should like to raise is the question of what I might call the means of self-defence for automatic exchanges. The exchanges are designed to carry a certain traffic, but that traffic is an average traffic. It may or may not be the average of the busiest times. Strictly speaking, I suppose, it should be the mean busy-hour traffic over the busiest season of the year. There are, however, times when abnormal events take place; there are periods of excitement such as elections, fires, races, accidents, etc. Occasionally there are cable breakdowns. On an automatic exchange these events are liable to cause overloads, resulting in considerable congestion. The group selectors are provided with means for dealing with congestion of that kind. The switch, if it cannot find a free outlet, runs over to the 11th position and remains there connecting the busy tone to the calling line. To bring about that state of affairs, however, the call must reach the group selectors and hold one or more of them engaged just at the time when it is most needed. It would appear to be very desirable to deal with overloads like this at the point where the line enters the exchange, namely at the line switch. This involves some arrangement by means of which false calls due to permanent loops and calls which cannot be completed owing to unusual congestion are thrown back on the line switch and held there, while all common switching apparatus is set free to help to cope with the overload. It would be useful if the author would indicate in his reply how a London exchange is arranged to deal with an abnormal load of the kind to which I have referred.

Mr. D. A. Christian (*communicated*): The decision, as recorded in the paper, to signal impulses round the loop in the case of junction circuits is one of far-reaching effect in the matter of circuit design generally. This is more particularly the case if othre signals, such as the supervisory signal, are also effected by loop signals. When signals such as that necessary to hold a call which has been made to an operator are also required, it would indeed appear impossible to retain pure loop working without introducing prohibitive complication. This latter meaning cannot, of course, be read into the decision given in the paper, and the London system does indeed employ leg signals for such cases. Mr. Morley Ward has already mentioned the advantage of increased junction resistance which accrues from leg signalling and has spoken of a system of impulsing over the two legs of the junction in parallel, which still further increases the workable junction resistance. A method of parallel leg working devised by myself may be of interest in this connection, as, in addition to increasing the permissible junction resistance, it also overcomes any fear of interference from variation of earth potentials or inductive surges induced from power systems. The principle involved is to arrange for impulses to pass over the junction legs in opposite directions, so that any interference from external sources strengthens the impulse in one leg while weakening it in the other. This method of parallel leg working lends itself readily to incorporation in a leg signalling and dialling system, based on the principles adopted in British standard manual practice. While the above arrangement offers a convenient method of overcoming possible interference with leg dialling from power circuits, I do not think that its adoption for this reason only would ever be justified. Mr. Bartholomew stated in his reply to the discussion on his paper* that the estimated lost-calls due to earth potential kicks would not be greater than 1 in 600 000, and that the degree of disturbance would have to be 60 times as great before the standard of the service would be sensibly affected. Even so, the loss of 1 call in 10 000 must surely be insignificant compared with the calls lost due to insufficiency of switches or other causes.

Mr. H. S. M. Hall (*communicated*): In connection with the dialling tone referred to by Mr. Laidlaw, there are, to my mind, more disadvantages of the present system than the one which he referred to, namely, the disregarding of the tone by the subscriber. These are: (*a*) If a fault develops on the subscriber's line, he will not receive the tone and will therefore assume that there is no apparatus available to receive his call—thus delay will be caused in reporting the fault; (*b*) the capacity of the dialling tone generator will have to be comparatively large as the tone will be connected in the greater majority of calls; (*c*) to an inexperienced subscriber the tone will indicate that the line is not clear and he will therefore refrain from dialling. I would therefore suggest that the present practice be reversed and the tone only connected when there is no apparatus available to the subscriber. This method would apparently obviate all the above disadvantages.

Mr. J. Hedley (*communicated*): Mention is made throughout the paper of certain essential conditions which have to be catered for in a large area such as London, and I should like to emphasize one or two points. The four essential conditions to which I wish to refer are: (1) Freedom of routing; (2) large groups of outgoing junctions; (3) large groups of private branch exchange subscribers' lines; and (4) satellite

* "Power Circuit Interference with Telegraphs and Telephones," *Journal I.E.E.*, 1924, vol. 62, p. 817.

working. The provision of the 500 line units in the panel system makes it inherently suitable for conditions (2) and (3), whereas in the director system with its maximum of 10 contacts it is necessary to provide special auxiliary equipment to meet these requirements. Even with the provision of this auxiliary equipment, the amount of number changing will be larger with the director system than with the panel system. In these two respects, therefore, the panel system has the advantage. In order to obtain this advantage, however, a non-decimal system has been adopted and consequently conditions (1) and (4) cannot be so economically catered for as in the director system, for the following reasons. In the case of " Freedom of routing," whenever a call arrives in a panel exchange a sender equipment or its equivalent is essential to accept, store, translate and route the decimal impulses for a call to any exchange and for any class of service as sent by the subscriber. It is interesting to note from a historical standpoint that the original design of the director, as exhibited to members of the Post Office Commission who visited America in 1922, dealt with the call in a somewhat similar manner, i.e. on the model provided for our inspection there were eight B and C switches on each director, so that each director was capable of routing a call for any exchange. In making the arrangements for the provision of a model in G.P.O. (West), I suggested that it should be designed to cater for the reception of the first digit sent in by the subscriber on a selector switch (now termed the " A digit switch ") which would route the subscriber to one out of a group of eight directors for the remainder of the call. These eight segregated groups of directors, which are approximately equivalent to one sender in the panel system, are capable of dealing with eight calls simultaneously instead of one in the sender of the panel system. This segregation keeps idle plant at a minimum and incidentally has enabled cross-connection facilities to be embodied on each director instead of through a common exchange intermediate distributing frame as in the case of the panel system. It should, perhaps, also be mentioned that this simple cross-connection scheme was developed by Post Office engineers. With regard to condition (4), a " satellite " exchange is one which depends upon a main exchange, termed the " parent," for the routing of its originating non-fee junction traffic, i.e. the satellite exchange will route direct its own originating local calls and also its own no-delay trunk calls via the toll exchange. It will be apparent that with an exchange designed on a non-decimal basis, as in the case of the panel system with its 500-line units, some equipment equivalent to a sender must be provided to accept, store, translate and route each call. For satellite exchanges, however, such sender equipment should be eliminated. With the director system designed on a decimal basis, all that is necessary is to allow all calls to be received at the parent exchange on directors used jointly by the parent exchange subscribers, and to arrange at the satellite exchange for discriminating equipment to function for the code of its own exchange and when " TOL " is dialled. Under these conditions the parent exchange will be set free, and the satellite exchange step-by-step plant will then operate direct from the subscriber's dial, i.e. there will be no directors provided at the satellite exchange. Circuit arrangements in director areas for such facilities have already been developed by Post Office engineers. In conclusion, I think it can be stated briefly that the main fundamental difference between a panel and director exchange equipment is that in the former the design caters for dealing with all service conditions at one point in the system, whereas the latter is based on designing the trunking scheme to arrange for the provision of plant suitable for the particular call at the most suitable point, i.e. the various classes of calls are summarized and converted into traffic units, and plant is provided accordingly for each particular requirement.

Mr. G. A. Hollings (*communicated*): Speaking as a village subscriber, I am disappointed to learn that so little is apparently being done for rural telephony. This branch of the telephone network is deplorably backward, and rural services are extremely bad. Half the exchanges of this country are rural exchanges, but in many of these there is no night service, and only a partial service is available on Sundays. In some districts the demand for service is refused altogether. Is it not possible in cases where the community is particularly small or remotely situated to install a very small automatic exchange, say from 5 to 10 lines, in a sentry box at the foot of a pole or in the local general shop? It is comforting to know that two Post Office rural automatic systems were installed last year. Presumably these plants were produced by the Post Office itself, but no indication is given as to the principle of their operation. Possibly they are the forerunners of a general scheme for rural conversion. Owing to the diversity of conditions in different countries it is rarely wise for one country to adopt the telephone practices of another, and, as we have seen, the Post Office has not considered it expedient to follow the methods especially suited to New York. I make this remark as I have observed, in the course of experience abroad, that there is a marked tendency on the part of overseas telephone administrations to accept the decisions reached in this country, without paying sufficient regard to the very special conditions that determine the trend of development here. Informed opinion is by no means unanimously in favour of the step-by-step principle; indeed it is suggested in this paper that this principle suffers from certain disabilities in comparison with other systems. Such systems as the Rotary, Relay and Ericsson have all passed with high honours the critical test of practical application. Each has its peculiar merits and claims: the Rotary for the positive action and robust construction of its contacting parts, the Relay for the amazing simplicity and almost motionless and silent action of its apparatus, and the Ericsson for the general beauty and excellence of its switch design. It is to be hoped that these systems will receive a full measure of practical support wherever automatic development is contemplated. The utility of dialling tone is open to question. In every 500 calls about six will fail owing to congestion at various stages of the switching, but only one of these failures will be notified to the calling subscriber. To sum the matter up, a busy subscriber who attentively listens for the dialling

tone on every call may expect to save himself the trouble, about once in 2 months, of performing a useless dialling operation on a call that is foredoomed to failure when the receiver is lifted. The gain is infinitesimal and it is safe to predict that this tone will be generally ignored. In view of the fact that there are three other infinitely more important tones to be interpreted, I think that it would be no loss if this one were suppressed altogether. It would appear that where a 20 000-line or 30 000-line automatic exchange is required it is customary to install two or three separate 10 000-line exchanges in one building. The factors that dictate such a subdivision of the plant are not clear.

Mr. G. Hurford (*communicated*): The ground covered by the paper is so extensive that one has to take for granted the general principles and curves mentioned. There are, however, a few points which are rather sweeping in character. The author states that the theoretical trunk-hunting capacity of 10-contact or 25-contact switches with secondaries would be increased to 100 or 250 circuits; I think it will be agreed that the 100 per cent efficiency of secondary switches indicated, although highly desirable, is never obtained in practice. I am inclined to believe that the author has this in mind as he states on the same page that "the theoretical method of attacking problems of switch layout is often exceedingly difficult and leads to results which are tedious to evaluate." The whole of section (5) gives one the impression that supporters of the large-capacity switch are working along wrong lines, as the author indicates that the same results can apparently be obtained with small-capacity switches combined with suitable grading schemes. Although grading can be used with beneficial results, its efficiency is always less than that of large-capacity switches with direct outlets. The author states that the panel system "has been installed to a capacity of more than 250 000 subscribers' lines." I am not quite sure of the meaning of the word "capacity." The first two panel offices placed in service were those at Omaha, and were cut over in January 1922 with approximately 13 500 lines equipped. In the same year four other offices were placed in service with a total of approximately 24 400 lines. A total of 58 full-automatic panel offices with over 400 000 lines equipped were in service at the end of February 1925. These figures include extensions to the original equipments. Of this number, no less than 24 offices with approximately 184 000 lines, i.e. nearly 75 per cent of the exchange lines in London, are now in service in New York City. The author states that the panel system is both costly and complex, but as he also states that the circuit arrangement of the director system is necessarily somewhat complex, one is led to believe that there is not very much to choose between the two systems on this score. A similar inference might also be drawn from the remark regarding the difficulties involved in training the requisite staff for handling the panel system, and the remark referring to the system for London, stating that automatic developments on so large a scale necessitate the provision of a very highly skilled staff to engineer, supervize and maintain the exchanges. Referring to the conversion of London to the automatic system, the author states that call-indicator equipments will be progressively thrown out of service during the period of transition. Studies of conversions of large areas have indicated that these equipments will go on increasing for a number of years before the maximum is reached. If the automatic systems for Manchester, Birmingham and Liverpool are to wait for call-indicator equipments to be recovered from the London exchanges, then I am afraid that any hopes that these towns may have of being converted to automatic in the near future are doomed to disappointment.

Mr. T. B. Johnson (*communicated*): On page 622 it is stated that "if the number of local calls which might be switched automatically will not exceed 3 000 per day within the 10 years' period, manual equipment will be installed without question." It would be interesting to learn the reasons which have caused this decision, as there would appear to be many cases within these limits which could be worked more suitably by automatic than by manual equipment. In the "border line" cases referred to it should not be overlooked that by the use of automatic equipment subscribers would obtain: (*a*) A more prompt response to calls; (*b*) a quicker reply from the called subscriber; and (*c*) immediate disconnection at the end of the conversation. These important advantages would surely justify the provision of automatic exchanges in all such cases. In the case of Keighley shown in Appendix I, it is obvious that the small balance of cost in favour of the automatic is due to the small proportion of local traffic and the comparatively large number of calls left to be dealt with by the manual operators. These calls are, however, chiefly over short-distance junctions, and on the introduction of a "time and distance" basis would all be removed from the manual operator, thus leaving a much larger balance of cost in favour of the automatic equipment. The same considerations doubtless apply to Maidstone and Macclesfield. An important point in connection with private exchanges is that the operating should not merely form part of some person's duties, but that a thoroughly competent operator should be employed, and that it should be her sole (or at least primary) work. In some cases junctions are held up because operators at private branch exchanges are engaged on other work. The time spent by operators in writing out-tickets for comparatively short-distance calls is so considerable, and the slowing-down of the operating so serious, that the introduction of a "time and distance" basis is urgently necessary. Operators should, as far as possible, be employed on operating only, and the introduction of other classes of work, such as ticket writing, avoided to the utmost possible extent. Although the expense caused by providing for the peak of the load is not so great in automatic as in manual work, it is appreciable. It is thought that reduced charges during the normal slack periods should be introduced, especially as a large number of manual exchanges will be in operation for many years to come. In one large manual exchange (which may be taken as representative of the whole) the calls rise from 600 between 8.30 and 9 a.m. to 4 400 between 10 and 10.30, dropping again to 1 200 at 1 to 1.30 p.m. and rising to 3 400 from 3 to 3.30 p.m. If by reduced tariffs during the slacker periods 1 000 of these calls could be

transferred from the peak hours, the number of operators could be reduced by 10, with corresponding savings in apparatus, wiring and space.

Mr. W. Johnston (*communicated*): The rapidity with which automatic telephony has developed, and the constant changes and advances in the art, have almost bewildered the ordinary telephone engineer who is anxious to do the best possible both economically and technically. The review which the author gives of the whole situation, and the reasons he sets out on page 636 justifying the choice of the step-by-step system for London, are most valuable. I doubt if he is fully aware of the important aid he has given to those outside the British Post Office service who are anxiously struggling with the subject of telephone engineering. On page 638 it is stated that decisions were taken to feed subscribers' talking and signalling current to the loop at final selectors or at outgoing junction repeaters and

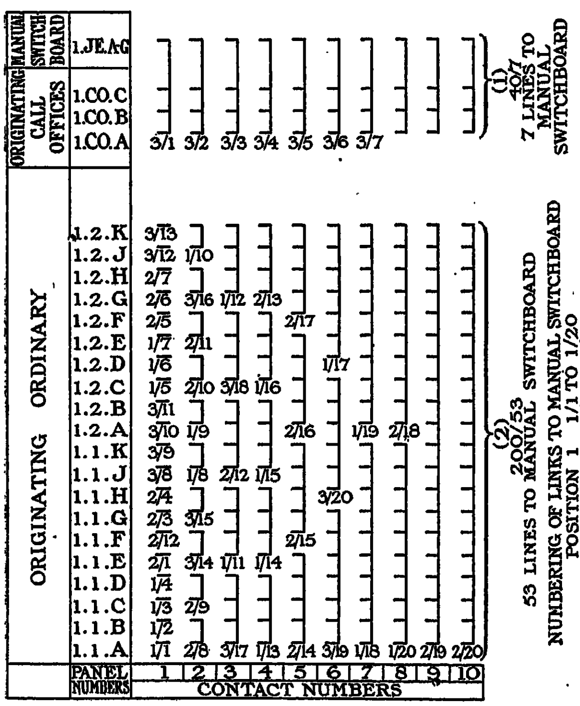

FIG. A.

that the registration on subscribers' meters was to be effected by means of a booster battery, whereas on page 642 this seems to have been abandoned and the system of feeding from the first selector and the simple metering adopted for London. Some years ago I had a Siemens equipment installed in Valparaiso with this system of feeding which seemed a step in advance, and I am glad to have this confirmed. However, the author still apparently retains the final selector feed for the called subscriber, and I am unable to understand the reason for this. With regard to grading, which is very clearly dealt with on page 627, I am glad to find that this is practically the same as arranged by Messrs. Siemens Brothers for the plant at Valparaiso. The gradings at Valparaiso are only between selector levels and do not take the place of secondary pre-selectors. A typical grading is shown in Fig. A, which is on the same lines as the arrangement set out in Fig. 12. It appears to me that the author must have some confirmatory data with regard to the statement on page 629 that "the grading scheme effects substantially the same economy as the use of secondary line switches." I should like to ask him if he could give the exact efficiency of grading as against second pre-selectors, which have given us every satisfaction and the faults on which have been very small indeed. Second pre-selectors should, by giving access to something like 100 selectors, be more efficient, and moreover the use of a 25-contact pre-selector would appear to increase the cost of an exchange both as regards apparatus and floor space.

Mr. E. A. Petithory (*communicated*): It is always interesting to look forward in telephony and, if possible, profiting by past and present experience, to anticipate the probable trend of events. This the author has, by his various decisions, attempted to do. In Fig. 14 is given a reproduction of an extract from a New York telephone directory, showing the method of listing the telephone exchange numbers in connection with the panel system. It is understood that this same method of listing is to be used in the London telephone directory. While this method appears to be, and probably is, very sound, the experience in the United States in cities using this type of numbering has been rather peculiar and in some respects undesirable. In a recent copy of the *Kansas City Citian* I observed that the majority of the advertisements gave no telephone numbers. This seems to be an adopted policy, as the telephone company's advertisement also gave no telephone number. Where telephone numbers were given some were printed correctly, i.e. two large letters followed by the balance of the exchange name, while others gave the exchange name in ordinary type. On one page was printed a large list of telephone numbers, and here the two first or initial letters only were given, the balance of the exchange name being left off, so that the exchange names became corrupted, i.e. MA for Main, etc. The same corruption is, I understand, also taking place in other cities in the United States, such words as "Center" becoming CEN. It is fairly obvious that the same thing is liable to occur in London. It would appear that the Post Office should endeavour to make newspapers and subscribers follow the telephone directory method and not corrupt the exchange names. Such corruptions on advertisements, letter paper, etc., will make it necessary for the user to look up the directory for the correct name, particularly when placing toll and trunk calls. On pages 654 and 655 the author refers to a suggested method of registering normal time units and illustrates a method of operating the subscribers' meters. From the experience that most telephone engineers have had with subscribers' meters, to work them in some cases 10 or 12 times during a call is not at all alluring from a life point of view; further, the interrupters with their various cams and attendant apparatus for switching in the meter impulse, etc., would probably be found to be very expensive. As a practical alternative I would refer the author to suggestions outlined in the

paper * by Messrs. Laidlaw and Grinsted, in which they outline the following method of metering, which eliminates all mechanical difficulties and would probably prove to be economical: "A simple apparatus based upon electro-chemical principles, the record depending upon the time it is in circuit and the strength of the current, which is regulated according to the rate at which the call is to be charged."

Mr. S. H. Pook (*communicated*): It is stated on page 646 that each call-indicator operator will handle 450 calls per busy hour, and that this is probably a conservative estimate. I think that it is very much on the low side. An order-wire operator can take this load, and call-indicator working is much simpler than order-wire working. I have recently seen call-indicator operators regularly taking a load of 500 calls per busy hour with ease, and under test it was found that they could go as high as 600 calls per busy hour. At this point difficulty was found, not from their being overloaded as regards operation, but from the cords becoming so interlaced that they were difficult to disconnect. This was with ordinary call-indicator working, but with the coder call indicator, as suggested for London, the interlacing difficulty should be eliminated to some extent, and it will not be surprising to find that a load of 600 calls will be looked upon as normal. The paper gives the impression that call-indicator working and the number of positions will be at a maximum at the outset. This of course is not so; it will increase considerably until a time arrives when roughly half the lines in the area are working on each system, after which it will begin to diminish. For an area we are at present investigating, the proportion between automatic and manual lines and the ratio of call-indicator working and of total exchange lines for three periods are as follows:—

* *Journal I.E.E.*, 1919, supp. to vol. 57, p. 158.

	Percentage of lines		Ratio	
	Auto	C.B.	C.I. working	Total exchange lines
At present ..	20	80	1·0	1·0
5 years hence ..	60	40	2·5	1·6
10 years hence ..	85	15	2·0	2·6

The well-defined maximum of auto-manual and manual-auto traffic means that at one stage it will be necessary to buy call-indicator and key-sending plant to take the peak traffic over the very short period, and it is under this condition that high loads on call-indicator and key-sending positions are desirable, as it is evident that it will pay to work at a maximum load, relieving the operators more frequently, for a small period in order to obviate the purchase of such expensive and short-lived apparatus. On page 622, annual savings of £14 000 in Sheffield and £7 000 in Newcastle are given. I should like to know if this is the average over the whole period or if it is the annual saving at the beginning or end of the design period, and also the number of lines involved.

[The author's reply to this discussion will be found on page 675.]

North-Western Centre, at Manchester, 17 March, 1925.

Mr. W. J. Medlyn: A few years ago the author visited the United States to investigate the telephone problems there and to consider the solutions applied; a considerable portion of the subsequent report naturally dealt with automatic telephony. The paper shows very clearly that the problem is full of complexities, as stressed by Mr. Herbert who has read the paper on behalf of the author, but no matter how complex the interior constructional design of the system may be, communication engineers, like electricity power supply engineers, aim to present the service which they purvey to the users, or consumers, in the simplest and handiest possible form for actual utilization. I suggest that the success of *any* system in common use depends on the fulfilment of this important condition. It is observed that the principles of economics are stressed throughout the paper; we appreciate that unless this important subject is continuously kept in view no commercial system can be successful. It would be useful to have some additional information in connection with the mechanical tandem exchange referred to on page 647. On reading the description one is left in a state of doubt as to whether during the transition period *all* the junction traffic between *all* the various exchanges in the London area will have to be circulated through the tandem exchange in the Holborn building, or whether this condition will apply only to the smaller groups of junction circuits. Had the former been intended the congestion of the junction cables would present a serious problem. The application of the automatic system to the telephone exchanges in the Manchester district affects us more directly than the introduction of the system in London. The same principles are, however, applicable in both cases, and plans for converting all the exchanges within a radius of 7 miles of the Manchester Town Hall are already well advanced. In Section (4) the author states that in areas of great telephone density it may be economical to establish two or more exchanges of 10 000 lines' capacity in one building. This condition applies to the city portion of Manchester. A site has already been acquired for the erection of a new building in Chapel-street, near to Exchange Station. This building will accommodate three 10 000-line units, i.e. three separate exchanges, and in the York-street premises similar capacity will be found for the conversion of the manual system to automatic. In addition to these six exchanges there will be 31 others within the 7-mile radius, making a total of 37, as compared with a total of about 74 within the 10-mile radius in the London area. The director system will be installed. The Stockport exchange, which is already automatic, will be modified to provide

equipment suitable for working into this system. The long-distance lines will continue to be terminated in the trunk exchange at the Head Post Office in Spring-gardens, but a " toll exchange " for intercommunication over the shorter lines connecting Manchester with the surrounding centres will be provided in the Chapel-street building. The telephone conditions in Manchester will therefore be identical with those which have been decided on for London as regards long-distance trunk exchange service, toll exchange service, and direct intercommunication between all subscribers connected with the various automatic exchanges in the local area. It is hoped that some of the new automatic exchanges will be brought into use in three or four years' time. The author mentions on page 644 that he estimates a period of about 15 to 20 years will be necessary to complete the conversion in London. Probably about the same period will be necessary to complete the work in the Manchester district. At the end of the paper the author touches on the question of the encouragement of home industries. It has recently been stated that the telephone industry in this country finds employment for upwards of 100 000 people, and it is gratifying to us to know that a goodly share of this activity is distributed among the business undertakings in the South Lancashire and neighbouring districts. Some of these undertakings supply apparatus equipment, cables, overhead wire, underground conduits, and storage batteries. It is satisfactory to know also that, in addition to catering for home supplies, these firms have been able to build up a considerable export trade.

Mr. H. H. Harrison: The " director," which is the outcome of the deliberations of many minds, has gone through a process of evolution. An early scheme embracing the use of switching selector repeaters operated as follows. If a letter, say M, was dialled, a group of trunks was seized going to all the exchanges whose first initial letter was M. As dialling proceeded, the junctions were discarded one by one until, finally, a free junction to the required exchange was the only one retained. This system had obvious drawbacks, the most serious being that a number of junctions were uselessly held until the third or discriminating letter was transmitted. The " universal switcher," as this arrangement was named, was quickly seen not to be the solution of the problem. The advantages of the " director " system appear to me to be as follows. The outstanding advantage is that the trunking scheme and the directory numbering are no longer interdependent. The director makes it possible to take advantage of the efficiency of large groups of trunks. That, of course, is due to the fact that one is able to extend the principle of tandem trunking. It is no longer necessary to provide, as formerly, for trunk groups from each exchange in an area to every other exchange in the same area. Tandem trunking can be carried out to an extent that would be impossible with a manually operated network. The " director " provides a simple means for re-routing calls when traffic conditions alter. This can be accomplished without changing the directory in the slightest degree. The only point of resemblance between the A B C dial sender shown in Fig. 27 and the calling dial which was used prior to the appearance of the Post Office standard dial, is the fact that it has radial finger-holds and is pulled round to a fixed stop. Beyond that all resemblance ceases. If the standard dial is examined it will be noted that in its operation two processes are necessary, a preliminary or setting process, and a subsequent transmitting cycle. The dial can be set at any speed within the operator's capabilities, but the dialled impulses are sent out at a regular rate. This last is secured by a small governor inside the dial mechanism. In the A B C sender, however, the setting and transmitting cycles overlap completely and if it is operated irregularly, which is almost certain to happen, wrong numbers will result. One other matter which deserves brief mention is referred to on pages 654 and 655. If a large area is divided into zones for tariff purposes the director possesses peculiar advantages. In a large exchange system without director facilities, the route is set up from exchange to exchange and differential metering is not easy to accomplish. With the director, however, the code dialled, and the digits into which it is translated, represent at the originating exchange that one and only one route is going to be taken; and a meter or meters can be operated in accordance with the route to be taken.

Mr. B. O. Anson: It is not unlikely that the first question to be asked by an inquiring mind would be: " Is a ' director ' really necessary ? " The reason for asking this question is that it would be quite possible to operate a telephone system with the dual purpose directory, enabling automatic subscribers to dial the code of the required exchange if the assumptions were made, (*a*) that every exchange had junction circuits to every other exchange, and (*b*) that the junction circuits were found on the banks of a train of switches corresponding to the numerical equivalent of the exchange code. These two assumptions immediately bring to light the important functions performed by the " director," for in the first place the provision of direct junctions from every exchange to every other exchange would preclude the adoption of tandem working, a most important aspect of automatic telephony. It would consequently commit the Administration to the provision of extremely inefficient junction networks often made up of very small groups of long circuits. To enable a subscriber to find junctions to the required exchange from the natural point on automatic exchange banks would mean that traffic would have to pass over six selectors, three for finding the junction and three for finding the required subscriber after the junction has been found. It will therefore be seen that the junction line would be sandwiched between two very expensive trains of switches, and the consequent design of such an exchange would be very costly. The importance of adopting a " director " is evident from the consideration of certain large metropolitan exchanges where as much as 75 per cent of the traffic may be to a very few neighbouring exchanges, say five or six, the remaining 25 per cent being spread over all the remaining exchanges in London. It is quite possible with the " director " system to hand over this 75 per cent direct to the junction lines by passing the traffic through only one rank of switches, namely the first code selector. As against that requirement we have, at

the other extreme, traffic that must pass through tandem exchanges because it is so small in volume. To permit of a wide range of conditions in this respect arrangements have been made for the "director" apparatus to send out as many as six trains of standard impulses. We therefore see that the three-letter code can be translated down to one train of impulses for very big blocks of traffic and translated up to five or six trains of impulses for very small blocks of traffic, and within these two extremes the practical problem is given its solution. In designing a manual exchange, attention has to be paid primarily to the operations performed by the telephonist, and for this reason the equipment is in the main based upon the busy-hour calling rate. With automatic plant, however, the designer must have regard to the average holding time of the call, as costly equipment is held engaged throughout the conversation. The speed and precision of an automatic telephone service are such that its superiority over manual service in large areas is undoubted and it is therefore reasonable to assume that, with a better service, subscribers will tend towards greater dispatch in their telephone service, and the telephone will play a greater part in their lives. This should mean that the average holding time for a call will fall, but, as the subscriber will not have less business to transact but in all probability more than in the past, the total calling rate should go up. It would follow, therefore, that the natural effect of good service should be shorter calls whilst producing more of them, and, as the plant is provided on the "holding time" basis and the revenue collected on the "calling rate," there should be a prospect of greater profit for a telephone administration under automatic than under manual conditions. Another factor that illustrates the advantage of automatic over manual service is the ratio of day traffic to "busy-hour" traffic. At a manual exchange a call must be operated whenever it occurs, and it costs more to operate a call during the night time and on Sundays than during the day time. With automatic equipment, however, it is necessary to provide plant to cope with the busy hour, but the equipment, once provided, is available to give service with equal efficiency day and night and there are no extra charges incidental to the night and Sunday calls, beyond the consumption of current. Whilst, therefore, the development of the telephone habit should produce a progressively greater proportion of traffic outside the busy hour, the automatic system will make that development more profitable than would the manual system. It is usual to assume that the automatic system would not have been adopted had it not "proved in" financially as compared with the manual system. The greater speed and accuracy of the automatic system, combined with the fact that the manual system rapidly deteriorates under heavy development because of the increased junction traffic incidental to development, makes the former so superior that its ultimate adoption can hardly be doubted, even had the annual costs been higher: subscribers would willingly have paid more for the better service.

Mr. J. Cowie: In the case of the common-battery manual system it is the operator who has to get the correct number, whilst with the automatic system it is the subscriber, and should a wrong number be obtained it is his own fault. I recently saw it stated that the advantages of the automatic system are: (1) Secrecy; (2) speed of call; and (3) instantaneous and automatic clearance of connections. These points will no doubt be clear after an examination of the demonstration set. In conclusion I should like to say that if the manufacturers in this country can deliver automatic telephone plant promptly when required, the Post Office Engineering Department has in its employment engineers, inspectors and skilled workmen who are willing and able to carry out the change from manual to automatic systems. They will do their work expeditiously, successfully, and with a minimum of inconvenience to the general public.

Mr. T. Cornfoot: I should like to say a few words from the subscribers' point of view. On page 617 in the introductory remarks the following statement is made: "In this economy of effort the subscriber has shared, and in modern 'manual' switching systems the only manipulative act required of him is that he should lift the telephone receiver from its rest before speaking, and replace it when he has finished." In the next paragraph the author says: "The adoption of the automatic system represents a reversal of this policy of economy of operation, so far as the subscriber is concerned, since it throws upon him the whole of the manipulation required to effect the ordinary local calls which generally constitute the bulk of his transactions." On page 622 the statement occurs: "Many authorities . . . argued that personal communication with the operator was necessary in order to reassure the public and to ensure proper use of the plant. To meet this frame of mind several systems known as 'semi-automatic' have been introduced." On page 621, however, the author, after reviewing the number of exchanges installed and the experience which the Post Office has had with them, says that it was also proved that the automatic method of working was generally acceptable to the British public. I read the other day that the conditions of the telephone industry are severe because all that the user can see of the complicated mechanism is a simple instrument, and while he is waiting for the operator seconds seem like hours and he becomes quickly irritated and forms wrong impressions as to what is happening, or rather what is not happening. It may be that the solution or cure for this is to allow the subscriber to manipulate his own call and to eliminate the operator altogether. Perhaps that is what the author refers to when he suggests that it has been proved that the automatic method of working is acceptable to the British public. If this is so, then the more completely automatic the system can be made and the larger the local fee areas the more satisfactory it will be. At the end of page 629 the author refers to a subject which has been widely discussed, viz. the method applied to the production of artificial traffic to calculate the total number of simultaneous calls at any one time during the busy hour. Telephone engineers seem here to have adopted a common-sense method of dealing with a very difficult problem.

Mr. G. H. A. Wildgoose: It is interesting to observe that after an extensive trial of automatic systems—there are eight systems mentioned in the paper—under actual working conditions, the Post Office has found no cause for regret. Again the statement, made by Mr. Cornfoot, that the British public has taken kindly to this method of working, is very encouraging. The experience in connection with the one public automatic exchange in Stockport supports this statement; the service was so acceptable to the public that the Post Office was compelled to make immediate provision for additional plant to meet the demand for subscribers' circuits. Previous speakers have alluded to the pending introduction of automatic working in the Manchester area. The preliminary arrangements in connection with this scheme have already given rise to several interesting problems. At the moment one such problem relates to the plant required to provide the necessary junction services, and it is assumed that the arrangements in general will follow those adopted for London. I think that has already been brought out clearly, but I should be glad of information on the following points: On page 623 it is stated that "junction circuits can be provided much more freely in an automatic system." On page 625 the author says: "The number of junctions required depends upon the traffic, which can be estimated from records of the traffic under existing conditions." It would be of some assistance to know whether, after determining the number of circuits which would be required on a manual basis, a multiplier is applied to ascertain the number which will be required under automatic conditions, and, if so, whether a different multiplier is used for various groups of junctions, toll circuits and trunks. Will the existing standards of transmission efficiency, so far as they are applied to the line portion of the circuits, be still maintained, or will they be modified in any way? On page 624 the author draws attention to the economy which will accrue from the introduction of the automatic system, and Mr. Anson has given very good reasons why the automatic system should be adopted, apart from the question of cost. It is interesting to note that the economy will be a progressive one, and it would appear that in about 20 years' time it will be somewhere in the neighbourhood of 30 per cent in favour of the automatic compared with the manual system.

[The author's reply to this discussion will be found on page 675.]

North-Eastern Centre, at Newcastle, 23 March, 1925.

Mr. J. R. M. Elliott: The first thought which occurred to me after reading the paper was the complete answer which it constituted, coming as it does from the head of a Government Department, to critics who have complained from time to time of the lethargy and apathy of the Post Office authorities in this country in recognizing the value of the automatic system of telephone working. The present paper alone, apart from the author's previous contributions to the literature of telephone practice, at once reveals him as the master mind behind the scenes in the complex problem of converting from manual to automatic the system of telephone working throughout the country. Of all the valuable information which the paper contains, not the least important in my opinion is that relating to the measure of standardization evolved by the Department, which makes it possible for each contractor to supply plant of his own type of mechanical construction. This will undoubtedly have the effect of promoting healthy competition, but one disadvantage associated with this arrangement will be that as the automatic system is extended, the mechanical portion of the equipment at exchanges will be of such a varied assortment as to make it difficult for maintenance workmen to become familiar with the details of each contractor's mechanism. This aspect of the matter will no doubt have been duly considered, but the author's views on the subject will be of interest. Much of the information contained in the paper is new to telephone engineers in the North of England, but we are not without practical knowledge of automatic equipment as we have experience of the working of the Western Electric rotary system at Darlington which was installed in 1914, and of the Strowger system at Marton near Middlesbrough. Then again we have three relay automatic private branch exchanges at works on Tyneside, and the results at all of these places have been eminently satisfactory. The author refers to substantial economies which are expected to result from the conversion of the plant in the Sheffield and Newcastle areas from manual to automatic. In this connection it may be of interest to know that it is intended to build in Newcastle three new exchanges, one in the centre of the City, one in the East end, and one in the West end, and this will involve the conversion to automatic of the exchanges at Gateshead, Gosforth, Benton, Wallsend, Dunston, Lemington, Blaydon, Hebburn and Whickham. Unfortunately, the site acquired for the central exchange, on which initial building operations were actually commenced some months ago, is required by the corporation in connection with a proposed new road, and it is probable that the difficulty which will arise in securing a new site will seriously delay the project as a whole. In addition to the provision intended for the Tyneside area, conversion from manual to automatic working has been decided upon at West Hartlepool, Hartlepool, Stockton and Middlesbrough. In bringing new automatic exchanges into operation in London, the author explains that the process is to be gradual, but in the cases of provincial areas of medium size involving a number of exchanges, in which Newcastle is included, the conversion is to be done simultaneously. In my opinion this is an unfortunate decision, as it will be many years in an area like Newcastle before equipment can be provided for all the exchanges concerned to permit of simultaneous conversion, and the public, who have for years been advocating automatics, will become more and more discontented with the magneto system, which they regard as being out of date. New Post Office buildings will shortly be opened at Gosforth and Gateshead and it was fully

expected that as a first instalment automatic exchanges would be provided in these two buildings. A simultaneous change-over from manual to automatic of a large number of exchanges in an area may be spectacular, but I am afraid that a considerable amount of initial confusion will be inevitable, as the method of calling will be new to subscribers and the exchange equipment will be new to the majority of our maintenance workmen. The matter is of such vital importance to those responsible for the conversion of an area, that I hope that the author may be able to give in explanation more information than is contained in the paper on the justification for simultaneous as against gradual conversion in an area in which several exchanges are to be treated. As the time approaches for the introduction of automatics at Newcastle, the need will arise for rearranging many of the telephone systems rented by the colliery companies in the counties of Northumberland and Durham. I may explain that in the early days of telephones in this part of the country, the keen competition which existed between the Post Office and the Telephone Company, coupled with the demands of colliery companies for intercommunication facilities between their offices, collieries, staiths, weigh cabins and other points, led to the establishment of a large number of complicated systems. The composition of many of the circuits on these systems is such that when they are extended to the trunk lines, and in some cases even the public exchange system, they constitute an inefficient link in the chain of communication in consequence of their transmission efficiency being inadequate for the purpose. Endless trouble from these sources is caused not only to the Department and the railway companies concerned, but to distant subscribers. The remedy is for these systems to have outlets to the various public exchanges serving the area in which these circuits are situated. This is a matter of considerable importance locally and it would be interesting to learn from the author the extent of the requirements of the proposed automatic exchanges so far as these colliery systems are at present constituted.

Mr. F. G. C. Baldwin: The paper indicates that during the past 15 years or so much valuable research and practical experiment in automatic working has been conducted by engineers of the Post Office in conjunction with engineers of manufacturers of telephone switching apparatus. The table on page 621 shows the steady development which has been going on in the installation of automatic exchanges. Expressing this development in another way, the approximate number of direct exchange lines connected to automatic exchanges was 14 000 in 1919, 16 500 in 1920, 17 600 in 1921, 17 700 in 1922, 19 000 in 1923, and 26 500 in 1924, while in 1925 the estimated number is 37 000. A result has been achieved which has never before been reached in the history of telephony in this country. I refer to the standardization of a system of telephone switching for the whole of the country, a feat which I think cannot be overestimated and which is bound to have far-reaching results in the future telephone service of this country. Standardization in telephony, through circumstances which there is no time to mention, has been but a dream of telephone engineers ever since the telephone was invented, but from what appears in the paper we now seem to be within measurable distance of obtaining it. In Fig. 4, 100 per cent of the number of subscribers are within a radius of 1 mile. I should like to know whether this needs some qualification, or whether it may be taken that the introduction of automatic switching has the economic effect of so placing the exchanges that the subscribers' lines are reduced in length to that figure. The paper deals specifically with large and densely telephoned areas, but in the table on page 621 three rural exchanges, which are of very small size, are included. I shall be glad if the author will say what prospect there is of the universal extension of automatic working in the country districts. One of the principal difficulties in connection with manually operated village exchanges is the question of operation and of night service as well as day service; there is also the question of accommodation. The introduction of automatic working would entirely eliminate the first-mentioned difficulty and give a night-and-day service equal to that of any other exchange. The principal difficulty met with in the provision of rural automatic exchanges is the supply of electrical energy, but perhaps the efforts of those engaged in the development of electric power supply in country districts may help in this direction.

Mr. C. Whillis: In connection with the system of grading described on page 628, is any attempt made to grade the subscribers in the groups of 75 on the basis of individual calling rates and thus further to equalize the traffic carried by the switching plant? It would appear that, apart from psychological difficulties, the director principle might be applied to the metering circuit in junction working to record the appropriate junction fee and thus obviate the intervention of an operator. If this could be done the amount of manual switching equipment in automatic exchanges could be very materially reduced.

[The author's reply to this discussion will be found on page 675.]

South Midland Centre, at Birmingham, 1 April, 1925.

Mr. G. Richardson: It is specially pleasing to learn from the paper that there has been such cordial co-operation between the Post Office experts and the experts of the large manufacturing companies in solving the many difficult problems that had to be considered. This close co-operation cannot be otherwise than beneficial to both sides in tackling the big task that lies ahead. I propose to give a brief outline of the scheme which the Post Office has in hand for installing the automatic system throughout the Birmingham telephone district, which includes the adjacent Black Country telephone areas. There will be four areas, namely, the Birmingham area, the Walsall area, the Wolverhampton area, and the Dudley area, each of

which will be unit-fee areas. When the conversion to automatic working has been completed, subscribers in each area will be able to obtain another subscriber in the same area by direct dialling over the automatic equipment. Calls to a subscriber in another area will require the assistance of an operator who will be placed at a manual board installed at the main exchange of each area. As regards the Birmingham area, which is, of course, the largest of the four, the first step to be taken will be the extension to practically double its present size of the existing large telephone building in Hill-street. This building work will be put in hand almost immediately. In the enlarged building will be installed two 10 000-line automatic exchanges, and to these exchanges will be transferred the present Midland manual subscribers and the present Central manual subscribers. These two exchanges will remain quite independent units, as they are at present. It should be noted that the present Central exchange building in Newhall-street will thus be made vacant. Further, as regards the Birmingham area, there will be five new automatic exchanges of a substantial capacity built in various parts of the city in positions which have already been determined by a close development study. These exchanges will not replace any of the existing exchanges, but will be additional. The positions of these additional exchanges may be roughly indicated by mentioning the following provisional names for them: Calthorpe, Bearwood, Harborne, Northfield and Aston. The building programme also includes fresh buildings for the existing exchanges, as in the majority of cases the present exchange premises are not suitable for the installation of automatic plant. I have already mentioned that the Newhall-street building, which contains the present Central manual exchange, will be vacated by the transfer of the Central subscribers to one of the 10 000-line automatic units to be installed in the enlarged Hill-street building. It is intended to utilize the Newhall-street building for the installation of a modern toll exchange, which will be readily accessible to all the subscribers in the four areas, and through which will be given a "no-delay" service to and from exchanges within a very wide area outside the Birmingham telephone district. Finally, the long-distance trunk service must be mentioned. In this connection it is intended to replace the existing trunk exchange at the Birmingham Head Post Office by a new exchange of the latest type, which will be operated in conjunction with the telephone repeater station. The repeater station has been in existence at Birmingham for some years, and at the present moment is being considerably extended. The proposals for the Black Country areas are also extensive. It is quite evident, I think, from what I have said about the proposals for the Birmingham area that the application of the system described in the paper means that we have a very busy time in front of us. The Post Office will need the co-operation of the building trades, and also the co-operation of the automatic equipment manufacturers, which, from past experience, I am sure we shall have in full measure.

Mr. W. C. Burbridge: Section (4) of the paper deals with the layout of the external line plant and exchange positions in an automatic telephone scheme and is of interest not only to telephone engineers but to all concerned with the best method of conveying electricity from source to consumer. It is obvious that large electric supply undertakings have to face problems which in broad principles are much the same as those concerned in telephone engineering, although they differ greatly in detail. The positions of generating and substations and the kind of main and distributive network must demand some kind of economic study, and I believe it is the practice to make calculations of some sort to determine the centre of gravity of an electric supply area. Is there, however, anything analogous to the detailed studies made by large telephone administrations? Does the electric supply undertaking have any method of forecasting the approximate number, class and location of potential users of electricity? Does it visualize the total or partial displacement of gas by electricity for lighting, heating and cooking, the places where, and the periods when, such conversion may be expected to accrue over a period of, say, 20 years? The Post Office does, of course, carry out very detailed studies of this kind. Such a study was made for Birmingham and the Black Country immediately before the war. It was overhauled in 1919 and used as the basis of the automatic schemes mentioned by Mr. Richardson. A general revision was made in 1923 and the forecasts are constantly being verified and amended. On page 624 it is stated that the costs of the line plant in London in 1945 under the automatic system would be nearly 30 per cent below those of a manual system. The amount of the saving is surprising, and I doubt if it could be paralleled in any city or district outside London. When it is borne in mind that the junction mileage under an automatic system is considerably greater than that under a manual system, it will be realized that the saving on subscribers' line mileage has to be enormous. That is, the area served by one automatic exchange must be very small compared with those served by one manual exchange. Now this means that there must be sufficiently large groups of subscribers on the boundaries of an existing exchange area out of which to form new areas. In other words, the telephone density on the fringe of existing areas must be great, approaching uniform density. Fig. 4 shows that such actually are the conditions in outer London, but it is far from being the case in Birmingham, or indeed, I think, in any large provincial city. Where there is not an approach to uniform density the approximations described in the paper are not likely to yield such a reasonable approach to accuracy as would enable sound conclusions to be formed, and other short-cuts have to be devised. I have referred to the increased mileage of junction lines in an automatic scheme. This is partly due to the multiplication of exchanges, but it is also a product of the routing of calls. Under the manual system, direct junctions between adjacent exchanges are the rule whenever the traffic is sufficient to justify it. As an illustration, Halesowen has direct junctions by the shortest route to Cradley Heath. Under the automatic system these places will be in separate automatic areas. Cradley will be in the rigid

numbering system of Dudley, Halesowen in the director system of Birmingham. Intercommunication by direct dialling between the two systems is not yet regarded as practicable; consequently Halesowen traffic to Cradley must circulate via the Birmingham manual exchange and the Dudley manual exchange. Notwithstanding this handicap, however, is it not the fact that an automatic system does effect direct economies in routing which go some may to balance this excess? Under the director system it should be possible to group the junctions from smaller outlying exchanges at some large exchange on the route nearer to the Central exchange. For example, the Victoria exchange in Birmingham is so situated with respect to two main cable routes that it could become the director exchange for six satellites, and so enable seven separate groups of junctions into Birmingham to be pooled into one group with an appreciable percentage of saving.

Mr. G. W. Billingham (*communicated*): With reference to the change-over from manual to automatic working in the Birmingham area, it may be of interest if I give a few facts relative to the external or line plant requirements. Unlike electric supply undertakings, the telephone requires a separate circuit to be provided for each line, irrespective of whether it is an exchange, extension or private line, and in order to provide continuous service during the preparation for the change-over dual lines must be provided, one line to the existing manual exchange and one to the new automatic exchange, which involves either entirely separate plant or lines in parallel. When such a conversion takes place in the same building, very little, if any, additional line plant is necessary. Where the exchange is situated in a new building near to the old exchange, additional line plant will be necessary, involving the laying of new ducts and cables, probably for a short distance only. The Central Birmingham case, however, presents difficulties of some magnitude from several points of view. From a scrutiny of the Birmingham maps it will be observed that the City is practically divided into two parts by New-street station and the railways running East and West. The telephone users on the North side considerably overbalance those on the South side. This is apparent from the fact that the Central exchange which serves the Northern portion has 6 000 direct exchange lines as against 3 000 on the Midland exchange serving the South side, the telephone dividing line between the two exchanges being New-street. In providing communication between the two exchanges and also cables for the subscribers' lines, there are four street routes available for our ducts and cable requirements, viz. No. (1)—route distance 770 yards; No. (2)—route distance 813 yards; No. (3)—route distance 1 130 yards; and No. (4)—route distance 1 220 yards. For economical and transmission reasons it is necessary that the route be kept as short as possible. Owing to the difficulties in obtaining a suitable site for a new exchange, it has been decided to house both Central and Midland exchanges in the existing Midland exchange, after considerable enlargement, and this building is situate in Hill-street. If it had been possible to utilize the Central exchange for the automatic requirements (for which, however, it is too small and impossible of enlargement), probably very little additional external line plant would have been necessary, but as in this case the greater load has to be added to the lesser a considerable augmentation of the existing ducts and cables between the two buildings will be necessary. It will be seen that this work will present considerable engineering difficulties when it is recognized that the roadway cover across the railway bridge in Hill-street is but 12 in. and this space is already occupied by Post Office plant, electric light, gas, water, and other public services. To lay additional ducts across this section on routes (1) or (2) at present appears impracticable unless arrangements can be made with the railway company to suspend a formation of steel pipes underneath the bridge from the girders, but it is at present doubtful if the clearance between the bridge and the rails will permit of this method being adopted. On route (4) the depth of cover across the Worcester-street bridge varies from 6 in. to 12 in., and last year it was found impossible to lay a further 6-way duct across, which necessitated a deviation via Bell-street to the Bull Ring. This route is too circuitous and costly to recommend its adoption for the extension of the lines from the central exchange to the new exchange at Hill-street. On No. (3) route the position is more favourable, as a tunnel only has to be negotiated on the top of which there is approximately 10 ft. of cover. The only difficulty likely to be encountered on this route is the congestion of service pipes at Broad-street corner, which may necessitate deep trenching and tunnelling to negotiate. Route No. (3) will probably be adopted although it will be necessary for distribution purposes to split the total number of ducts entering the automatic exchange building between the front entrance in Hill-street, and the back in John Bright-street. On completion of the duct lines the cabling work presents little difficulty. As previously mentioned, it is necessary during the progress of the work to provide continuous service, and the extension of the existing lines has to be carried out with extreme care and caution to avoid interruption of the service. The preliminary cable work will consist principally of teeing all circuits into the automatic exchange in order to test and prove out every circuit and to make a clean-cut change-over of probably 10 000 circuits by means of direct tee joints, or by transfer strips temporarily provided at three exchanges, viz. Central, Midland, and Automatic. The tee connections will be made at four principal points, viz. Broad-street corner, Temple-row, Worcester-street, and Midland exchange. Apart from the laying of the ducts and cables, considerable jointing work will be necessary and it is anticipated that about 24 jointers will be permanently employed on this work for at least six months. About half a million wire joints and tees are involved and each circuit will have to be identified and proved at each cutting-in point. The details of the work involve a considerable number of consecutive operations, each one depending upon the others being absolutely correct. These jointing operations are all set out on schedules and blue-print diagrams before the work is commenced.

The Author's Reply to the Discussions before The Institution and at Manchester, Newcastle and Birmingham.

Colonel T. F. Purves (*in reply*): I recognize that my paper contains a good deal of technically contentious matter, regarding which it is out of the question to expect universal agreement, and I appreciate the generally helpful and constructive character of the comments made upon it by so many speakers and contributors.

I agree with Mr. Laidlaw and Mr. Hollings that a considerable proportion of subscribers will probably not listen for the "dialling tone" before making a call, at least in cases where the tone is a subsequent addition to an automatic system with the operating of which they have already become familiar. But when the tone has been a feature of the system from their first acquaintance with it—and this will apply to the great bulk of British subscribers—I think it will be used much more systematically, even if in more then 95 per cent of the cases no trouble will arise from ignoring it. If a call has, for any reason, been ineffective, and the familiar ringing signal is not heard, subscribers will generally learn to listen for the dialling tone before making a second attempt. The tone is also very useful if it is desired to originate a call immediately after completing an incoming call from a private branch exchange, or from a manual or trunk exchange, as its presence is an indication that the connection has been cleared by the operator and that the line is again available. I may remark that the dialling tone is produced by the simple interruption of a battery circuit by an additional running commutator on the general tone-producing machine. There are no difficulties, and little expense, involved in its provision. Mr. Hall suggests that the tone should only be audible where a primary outlet to connecting plant is not available, but under these conditions its presence would be such a rarity that its meaning would probably be forgotten altogether or be confused with that of the "busy" signal. I think it is preferable to utilize the tone as a positive indication that the line switch has found an outlet and that calling conditions are normal. The fear that a subscriber whose line is faulty may assume that the absence of the tone indicates non-availability of outlets, and may therefore refrain from reporting the fault, has not much foundation; subscribers speedily become familiar with the many audible indications that a line is "alive," as compared with the "dead" condition of a faulty line.

Mr. Nash makes a kindly and generous reference to the amount of work and responsibility which has to be shouldered by the Post Office engineering staff in connection with such questions as the equipment of the London telephone system with automatic plant, and I greatly appreciate his expression of confidence in the success of the system which has been adopted. At the time when I had to take my courage in both hands and decide to turn away from the practice of the great American Bell telephone organization, for whose example we have so high a regard, I should have been very gratified indeed to know that, even before our first exchange had been installed, one of the leading engineers of the Western Electric Co. would so express himself. Mr. Nash presents an interesting table in which the number of secondary selecting switches, which would provide full trunking availability, is compared with the additional trunks required to furnish the same standard of service by means of 10-contact switch levels on a direct, graded, basis. I agree that a perfectly satisfactory circuit for secondary pre-selecting switches has not yet been forthcoming, although some telephone administrations appear to be prepared to adopt secondary switches to a considerable extent. Their use, of course, introduces additional switching points which undoubtedly complicate the tracing of calls and, to that extent, hamper the work of the maintenance staff. It is not easy to visualize the service-degrading factor introduced by outgoing secondaries, but it is obvious that without such devices the system is cleaner and easier to maintain. It is felt that the present system introduces quite enough complication and innovation for the maintenance staff to assimilate at the outset, but the Post Office has by no means "burned its boats" in this matter. The economies due to the utilization of large groups of selectable junction circuits, and the possibilities presented by the use of secondary switches as a means to that end, are fully appreciated. In the first automatic exchange installed in London, provision is being made for associating outgoing secondary switches with junctions to selected exchanges, so as to obtain actual working experience in the handling of junction groups up to a maximum of 100 lines. If satisfactory service is afforded by this method, there will be no hesitation to adopt it in cases where the overall annual charges will be sufficiently reduced by so doing, which are, of course, likely to be those cases in which the junction circuits are long and of heavy gauge.

[I have had Mr. Nash's calculation of the amount of plant required—with and without secondaries—to handle 35 traffic units carried a little further, and it may be of interest to give the results. The full debit of variables, to each system, would be as follows :—

Graded Scheme.	*Secondary Scheme.*
81 Junctions	114 Secondary switches
81 Incoming selectors	61 Junctions
	61 Incoming selectors.

On this basis the balance of annual charges is in favour of the graded scheme for junction circuits up to about 4 miles in length. For circuits over that length it would pay to employ secondaries. The average length of junction circuits in the London area is less than 4 miles, and the average length of junctions between the main exchanges is a much smaller figure, so that the economic balance is at present in favour of grading as a general policy. But in practice the use of secondary switches would probably be combined with the grading system, and consequently it might not be necessary to employ so many as 114 secondaries. The use of 25-point secondaries would also tend to reduce the

number of junctions and incoming selectors necessary, and, neglecting for the moment the various disadvantages of secondary switches, the economic balance might be so shifted that the use of secondaries would represent a saving where the length of the junction circuits is appreciably less than that quoted above. The number of junction circuits in the group also affects the comparison. It will be appreciated that the use of 20-contact selector banks would materially alter the basis of the calculation in a sense more favourable to grading. As already indicated, the whole question is being closely studied.]

Mr. Morley Ward inquires as to the reason for the adoption of the plan of sending dial impulses around the loop of a junction circuit, instead of over one conductor of the line or over both conductors in parallel. Mr. Christian also refers to the same point. This matter was given very close study, as it was fully realized that the adoption of loop-impulsing would mean a considerable reduction in the permissible maximum resistance of junction circuits, and that, with the impulse-receiving relays at present available, it would in some cases involve the use of heavier-gauge junction circuits than would have been necessary from the standpoint of speech-transmission efficiency. The main consideration in favour of loop-impulsing is, of course, that it provides security against the inductive interference of power and lighting circuits with the telephone signalling impulses. Tests were made from the Central exchange, to various points in London, by means of recording apparatus connected in earthed circuits. The records showed a certain amount of inductive interference, although surges of sufficient magnitude to affect dial signalling were so rare that it seemed improbable that they would in general affect the number of call failures to any recognizable degree. It was felt, however, that abnormal conditions due to faulty power circuits might sometimes cause more or less acute local trouble, and also that the general development of electrical supply systems, and of railway electrification in London and throughout the country during the next decade, might, in spite of the statutory safeguards of the Post Office against prejudicial interference with its communication services, have the effect of progressively worsening the conditions. It was therefore thought desirable to standardize, from the commencement, a system which would enable the department to demonstrate, in any case of trouble, that its own plant was so constructed as to secure the greatest possible immunity from outside electrical interference.

I am glad that Mr. Morley Ward mentioned the early pioneer work of Mr. William Aitken in connection with the invention of multi-choice grading: this might well have been referred to in the section of the paper dealing with that subject.

Mr. Carter and Mr. Harrison both refer to the ingenious pre-director development known as the "universal switcher." This system was the subject of interested attention by the Post Office, but we did not at any time feel inclined to adopt it. In addition to the wasteful use of junction plant, which both speakers mention, it required a completely predetermined numbering scheme, and therefore did not obviate some of the main difficulties involved in the introduction of an automatic scheme in large multi-office areas.

Mr. Deakin has given much information that is both interesting and valuable to a student of the subjects he refers to. I am not quite sure that, in his references to the method of grading illustrated in Fig. 12, he is not overlooking the fact that the advantage of grading from 24-point pre-selectors is not merely the 15 per cent increase obtained in the traffic-carrying capacity of the first code selectors. By suitable selection of subscribers' lines for connection in each group of 75, and by grading as indicated, the large block of traffic originated by 1 200 subscribers is turned over with approximate uniformity to the outgoing multipled circuits of the selector groups. It is thus presented to the succeeding graded ranks of switches in more manageable form, and the effect of this is to improve the carrying capacity of these subsequent switches, as well as that of the first code selectors. Special traffic curves making allowance for this fact are used in designing the layout of automatic exchanges. The maximum increase in traffic-carrying capacity that can be claimed for ordinary grading from 10-point selector banks throughout the switching system is about 30 per cent. It should be noted also that a graded system using 20-point selector banks has still to be studied, and that this may modify the economic comparison with outgoing secondary switches. A factor to be borne in mind is that the largest groups of junctions are required between large exchanges and that such exchanges, in London, are fairly close together. The circuits in these large groups of junctions thus tend to be both short and of light gauge, and their cost is correspondingly low. As regards tandem working, it should be remembered that the mechanical tandem exchange is being introduced to supersede the direct trunking of small groups of three or four lines. The change from these very inefficient groups to groups connected on a graded basis to 10-point contact banks represents a very material advance.

As regards the system of service to be adopted for communication between manual and automatic exchanges, it must be recognized that a system which may be specially adapted at the outset to requirements may be unsuitable at later stages. There is no question that the most convenient method of equipping the first group of automatic exchanges in London is the provision of "Cordless B" positions, but a time will no doubt come when it will be economical to install sending equipment at the "A" operators' positions in the remaining manual exchanges. A study of the comparative economics of dials and key-senders for this purpose has been scheduled for attention in due course. It may well be that considerations of space available in the different manual exchanges will dictate treatment of each on its individual merits. A powerful factor in favour of key-senders will always be the fact that the introduction of these high-efficiency devices reacts favourably on the load which can be carried by "A" operators, and has the effect of increasing the traffic-carrying capacity of manual exchanges and avoiding the extension of obsolescent plant.

I am rather surprised by the emphasis with which Mr. Deakin depreciates order-wire working in general, in spite of the fact that I have always had a decidedly soft side for the alternative of a properly developed direct trunking system. I can assure him that, although his remarks may be justified from the experience and practice of some administrations, they do not apply in this country, where the order-wire system has always proved reasonably satisfactory. The system has to be kept clean; split order wires and tandem order wires are things to be avoided, and perhaps these points have been ignored by those administrations in whose service he reports that the system has been "a dismal failure."

Mr. Grinsted has brought into prominence the very large number of separate switch movements, and circuit openings and closures, involved in the setting up of a connection in the automatic system. It would, indeed, be a hopeless mental task, even for the most expert automatic engineer, to visualize all that is taking place during the few seconds he is engaged in turning in a call on his telephone dial in a "director" area. The figures Mr. Grinsted produces show in a striking way the extreme need for the most efficient maintenance of exchange plant.

His suggestion that congestion at the switches might be minimized by some method of instantaneously throwing back, to the incoming line switch, false calls caused by permanent loops due to line faults, as well as "busy" calls blocked at any point by traffic congestion, is legitimate and the subject is well worthy of attention. It has, indeed, already been considered very carefully, but no way of effecting the desired result has yet been found without involving an additional circuit complication which has to be repeated so frequently throughout the exchange that it is not considered desirable to introduce it at present. The aggregate switch occupation caused by "busy" calls will probably not be great, as the subscriber will in most cases release the switches at once by restoring his receiver to the switch hook. False calls due to faulty lines can, with a proper system of alarms and guide lamps, speedily be traced back to the main distribution frame and there plugged out. The London exchanges are therefore being arranged to deal with abnormal loads of this kind by the ordinary supervisory methods of maintenance hitherto employed at all automatic exchanges.

Mr. Hollins has touched upon one of the disappointing features of automatic telephony, namely, its failure to provide economically for rural telephone service. Mr. Baldwin also referred to the same point. This subject is not altogether within the scope of the paper, but I may say that continuous attention is being paid by the Post Office engineering department to the special problems of rural automatic exchanges. Even at the smallest automatic exchange it is necessary to have a few costly fundamental items for the use of all the subscribers in common, and when the number of lines is small the cost per line of these general items is very high, especially if an electrical power supply is not available. It is then necessary to install an engine and secondary-cell-charging machine, with comparatively high capital and maintenance costs. These restrictions represent part of the price which this country has to pay for its low general development of the use of electrical energy. The extension of rural automatic exchanges will probably follow rapidly on the extended distribution of electrical power in rural communities.

I have already referred to Mr. Hollings's remarks on the subject of the dialling tone.

Mr. Hurford has taken rather too literally my round figures of the increase in trunk-hunting capacity secured by the use of secondary switches; I quite agree that 100 per cent efficiency could not be obtained in practice. Actually the efficiency of, say, a 10-point primary pre-selector, working into a 10-point secondary pre-selector, may be taken as approximately 85 per cent.

I am sorry if Section (5) of the paper is calculated to give the impression that designers of large-capacity switches are thought to have been working along the wrong lines. This inference was certainly not intended to be drawn in any general sense. Indeed, in Section (9) I say that the facility for direct selection in large groups is a feature of great utility which was reluctantly given up on account of its essential incompatability with the system which had been adopted for standardization in this country on broad considerations of preponderating advantage. My statement of the capacity of panel automatic exchanges in the service of the American Telephone and Telegraph Co. was based on a summary of the position, prepared in America, which I receive every six months. The latest summary referred to the beginning of this year and included 53 exchanges, with total equipment for 273 167 lines.

Mr. Hurford states that his much larger figures (58 exchanges with capacity for more than 400 000 lines) include extensions to the original equipment. It therefore seems probable that the summaries in my possession represent the line capacity of each exchange as it stood at the date of the "cut-over."

I quite agree that the amount of call indicator equipment in London will go on increasing for several years before it passes the maximum and begins to become surplus. Mr. Pook also makes a reference to this point. The amount of such equipment used in any particular manual exchange will, of course, steadily increase until the exchange is converted to automatic working, and therefore the last exchange to be converted will have the whole of its "B" positions equipped with call indicators. There is no intention that the initiation or the progress of the conversion of provincial city areas to the automatic system should be in any way dependent upon the rate of recovery of surplus call indicator apparatus in London.

Mr. T. B. Johnson gives figures which illustrate the exceedingly "peaky" traffic loads of the British telephone system. This condition, which I think is without parallel in any other administration, seems to imply that the effective business day in this country is an exceptionally short one. It has a very prejudicial effect upon telephone economics, and justifies careful study of the possibilities of improving the load curves by the skilful manipulation of varying tariffs. The advantages of the automatic system which Mr. Johnson enumerates are, of course, fully admitted and would be sufficient to turn the scale in its favour in many

cases where the manual system shows an economy from the strict financial standpoint of annual charges. The general conditions (given in the paper) which at present determine the use of manual or automatic plant are based entirely upon economic results. At the moment the demand for automatic plant is greater than the supply and, in order that the available product of manufacturers may be utilized to the best advantage, it is necessary to install a considerable amount of manual plant. The line is therefore drawn at a point which excludes from automatic treatment cases not financially advantageous, and as a rule these are also the cases where the service advantages of the automatic system over the manual system are at a minimum.

In reply to Mr. W. Johnston it may be said that the location of the calling subscriber's battery feed at the first code switch is a special arrangement made practicable by the traffic conditions usually found in "director" areas. The general location of the talking and signalling bridge on the outgoing repeater or final switch is a consequence of the adoption of loop signalling over junction circuits. The statement that a good grading scheme effects substantially the same economy as the use of secondary line switches, is intended to be an expression of the general economic position resulting from the adoption of grading as a policy. There may be points in an automatic exchange where the use of secondary switches would be more economical than grading, but, in general, the reason for not adopting the secondary switch is a service one rather than a financial one, particularly with reference to the use of such switches in external junction circuits. The reference in the paper was made with particular regard to the conditions of Fig. 12, which apply to 25-point pre-selectors, and it is certainly not economical to utilize 25-point secondary pre-selectors instead of grading.

Mr. Pook expresses a hope that the effective busy-hour load of call indicator operators will much exceed the 450 calls quoted in the paper, and it is quite reasonable to anticipate that this will prove to be the case. The load figure of 450 calls per busy hour was adopted for purposes of design in order that there should be no question as to the adequacy of the plant in the early stages of the change of system in London. The estimated annual savings of £14 000 at Sheffield and of £7 000 at Newcastle-on-Tyne consequent upon the introduction of the automatic system were calculated upon the estimated number of lines in all the exchanges in each area at the opening date, i.e. 8 800 lines in Sheffield and 10 000 lines in Newcastle.

Mr. Medlyn in the course of his valuable comments asks on what principle junction circuits will be worked through the mechanical tandem exchange. The intention is to serve the small manual exchanges, referred to in this section, almost entirely through the tandem exchange, unless, after their conversion to automatic, some other automatic switching centre should be more conveniently placed to serve them permanently. With the exception of a few direct circuits to exchanges in close proximity, all the incoming and outgoing junctions of these small exchanges will therefore be taken to the tandem exchange. The other exchanges in the area—both manual and automatic—will each be provided with a group of incoming and outgoing junctions to the tandem exchange sufficient to carry their traffic to and from the small exchanges. Some exchanges of medium size which are comparatively widely separated, and have a very small interchange of traffic one with another, will also obtain connection via the tandem exchange. As every manual exchange will have positions fitted with call indicators actuated from the cordless "B" boards at tandem, the existence of this exchange clearly provides facilities for concentrating general inter-exchange traffic on the tandem junctions during slack periods, and this facility will be utilized as a convenient method of enabling ordinary "B" positions to be closed at such times.

Mr. Harrison is not quite satisfied with my more or less whimsical claims for the old-fashioned telegraph ABC dial sender. It is true that in the modern automatic dial the operations of setting and of impulsing are separated, and that no dial could be generally used to operate an exchange system successfully unless the speed of impulsing were thus removed from the direct control of the individual who manipulates the dial. But this independent control of the impulsing speed is no part of the main claim of the original master patent, and the fact that the old telegraph dial would, if produced, have clearly anticipated the patent remains unshaken. Actually I have used this old dial quite successfully for making calls on a telephone automatic system, and I found it quite easy to ascertain and adhere to a sufficiently accurate speed of rotation.

Mr. Wildgoose inquires whether the number of junctions required under automatic conditions is derived by an agreed multiplier from the number previously in use in the manual system. In practice no such comparison is made. The number of junctions needed between each pair of exchanges in the automatic area is calculated directly from the traffic data, on the basis of one lost call in 500. The existing line transmission-standards are worked to without alteration when designing the layout of external plant in an automatic area.

Mr. Elliott expresses some apprehension lest the postponement of complete standardization of apparatus will lead to difficulties when maintenance men are transferred from one exchange to another. I do not think that appreciable trouble need be feared from this cause. The product of the various manufacturers differs only in self-contained detail, which will speedily become familiar to a man who is well acquainted with the standard electrical plan of the system. It is anticipated that it will be possible to arrange a satisfactory basis on which each contractor will provide for subsequent extensions to all exchanges which he has originally installed, as has hitherto been the rule with manual exchanges. The existence of diverse types of equipment at the same exchange will thus be avoided. Mr. Elliott also queries the wisdom of arranging for a simultaneous transfer from manual to automatic working at all the exchanges in an area of medium size such as Newcastle-on-Tyne. There is much to be said on both sides of this question. Simultaneous transfers involve a large amount of difficult co-ordinating work, but it has been concluded that as a rule the balance of advantage is decidedly in favour of this plan wherever

it can possibly be followed. A great amount of long-drawn-out temporary work and the provision of temporary auxiliary plant for interchanging automatic and manual traffic during the interim period is thus avoided. In the particular case of Newcastle the central automatic exchange, and the manual board for the whole area, will, on account of the building situation, mature at a later date than the other exchanges, and much wasteful provision of temporary equipment, which probably could not be justified financially, would be involved in an attempt to introduce automatic working at the smaller exchanges while the central exchange remained manual. But I shall have the case of Newcastle re-investigated before action is taken.

Mr. Baldwin has called attention to a point in connection with Fig. 4 which has not been clearly expressed in the paper. Subscribers outside a radius of one mile are excluded from the graph, the description of which ought to have been—" Number of subscribers within various radii, up to one mile, shown as a percentage of subscribers within 1 mile radius."

In reply to Mr. Whillis's inquiry regarding Fig. 12, it should be stated that the subscribers connected in each multipled group to the line switches are so selected, in accordance with their average calling rates, that each group will carry approximately the same amount of traffic. The grading arrangements on the outgoing link frame are made on the assumption that practical uniformity in this respect has been secured.

I have to acknowledge contributions to the discussion by Mr. Aitken, Mr. Collyer, Mr. Hedley, Mr. Petithory, Mr. Richardson, Mr. Anson, Mr. Burbridge, Mr. Billingham, Mr. Cowie and Mr. Cornfoot, which contain much information and much welcome and valuable constructive matter, but which do not appear to call for any specific reply.

DISCUSSION ON "SELECTION OF BALL AND ROLLER BEARINGS FOR ELECTRICAL MACHINES." *

NORTH MIDLAND CENTRE, AT LEEDS, 24 FEBRUARY, 1925.

Mr. H. Green: As manufacturers of rotating electrical machinery we find that ball and roller bearings give exceedingly little trouble. I do not think that we have had on something like 5 000 machines supplied within the past five years five cases of trouble due to ball bearings, and I feel confident that for small dynamos and motors ball and roller bearings are right. A number of breakdowns are due to the fact that many of the bearings fitted are too light, and although the author gives certain formulæ it is not usual for a designer—of small motors and dynamos, at any rate—to know the load which may be applied. If an ordinary ring-lubricated bearing is overloaded it becomes hot and calls for attention, whereas a ball bearing shows no sign of overloading until it is damaged. I have in mind a large double belt fitted from a motor to a line shaft. The belt was at least twice as strong as necessary, and the belt splicer naturally fitted it as tightly as possible, with the result that the bearing was fractured. It will therefore be seen that with ball and roller bearings it is necessary to have a big margin of safety.

Mr. F. Parkinson: Prof. Goodman's experiments have shown that theoretically a ball bearing is in effect a point contact incapable of lubrication. In practice it is found that a lubricant is useful for serving the dual purpose of providing a lubricant for the cage and also for preventing rust or acid attacking the case-hardened faces of the balls or ball races. There is much misconception on this question of lubrication of ball bearings. My own firm in their assembly of ball bearings make no provision for lubricators. This practice is based upon experience, as I believe that the experience of ball-bearing manufacturers is that more damage is done to bearings by the use of the wrong quality of grease than by omitting lubrication altogether. If a Stauffer grease cup or other means of filling the bearing housing with grease is provided, the tendency is for the attendant to supply new grease periodically whether it is required or not, and very often this grease is not entirely free from moisture or acidity. The lantern slides shown by the author raise another point in regard to this lubrication problem. They show elaborate arrangements for retaining the lubrication, but if our ideas are correct these elaborations are entirely unnecessary. We claim that the correct way to grease the bearing is to fill the housing with a grease of the correct kind for the purpose and then to seal the housing completely so that no grease can escape. To achieve this we have patented a special housing, and our experience, which covers more than 10 years, is that there is absolutely no necessity to replace this grease. Many instances have been brought to our notice where motors have been in constant operation day and night for more than 7 years without the bearings being touched in any way, and no new

* Paper by Mr. T. D. Trees (see vol. 62, p. 782).

lubrication has been supplied. If for any reason it is necessary to take the motor apart for general cleaning purposes, then obviously the proper thing to do is to wash out the bearings with paraffin, fill the housing with new grease and seal up. We claim that the sealed housing for bearings is an essential feature to ensure complete success. The second point that occurs to me is based upon an experience which dates back 15 or 20 years with a certain well-known make of motor. At that time it was the practice to fit ball bearings on turned motor shafts, and many cases of serious trouble occurred due to the shaft creeping inside the ball race. This wore down the shaft and allowed the rotor to foul the stator. A turned shaft when examined under the microscope will be found to consist of a number of ridges due to the cutting tool, and when a ball race is pressed on such a shaft the effect is to shear off the tops of the ridges. The consequence is that the area of contact between the inner race and the shaft is reduced very considerably. In designing our machines we benefited by the earlier experience of our competitors who had used turned shafts, and we formed the opinion that the correct application of ball and roller bearings to a motor shaft involves grinding the motor shaft to the same close limits as those to which the ball bearing itself is made. The results of the correct fitting of ball bearings and the correct housing of ball bearings are remarkable, as out of over 60 000 motors fitted with ball and roller bearings our experience is that not one machine in 10 000 has given any trouble due to the bearings.

Mr. H. Moss: I gather that in the author's opinion the bearings fitted in many machines to-day are inclined to be on the small side, or the light side, for the amount of work they have to do. If that is so, is that the cause of the ultimate failure of the machine? For a motor or dynamo manufacturer to fit a bearing that is smaller than it should be seems to be a foolish policy, because the cost of the bearing would be only a small percentage of that of the machine. Buyers and sellers of these machines would like to know that the manufacturer is putting in a bearing suitable for the work it has to do. Mr. Parkinson raised a point which seemed to be somewhat at variance with the paper. A large number of lantern slides have been shown illustrating different methods of lubrication, yet a user or manufacturer of long experience like Mr. Parkinson has supplied thousands of machines and does not find it necessary to provide any means to lubricate those machines. If it is not necessary to provide lubrication or any means of renewing it, why do manufacturers continue to make those provisions? It is adding to the initial cost and leaving openings for dust and dirt to get in by inserting a lubricant which may not be suitable. It would have been of interest if the author had touched upon the type of lubricant or grease that should be used for ball and roller bearings. As there seems to be such a difference of opinion between the manufacturers of bearings and the manufacturers of machines who must be using thousands of those bearings, it is difficult to determine whether the bearing manufacturer or the motor manufacturer is right.

Mr. R. J. Mitchell: The author would like to stereotype the question of the sizes of bearings for the rather vast range of electrical machines which the British electrical industry manufactures to-day, and doubtless that is a counsel of perfection, but it appears to be a fact that the modern engineer is so busy with his own job, and often so much obliged to become a specialist in two or three branches of knowledge, that he hesitates to add further branches to his list of specializations. The result is that in our opinion he acts very wisely when he consults the ball-bearing manufacturers and to a considerable extent follows their advice. He is perfectly safe in a commercial sense in so doing. The infinite care taken by manufacturers to do their utmost not to mislead the user on the choice of bearings cannot be too strongly insisted. It comes to this: If the growth of the industry is to continue in the satisfactory manner in which it is now developing, it will be far better for engineers generally to go to the bearing manufacturers and give them all the trouble—which they are very willing to take—of examining the proposed application, and in such cases giving the bearing manufacturers the fullest possible information about the mechanism into which it is proposed to install the bearings. The calculation of load capacity appears to be a subject of infinite difficulty. Palmgren wrote a most elaborate paper on the load capacity of ball bearings, at the end of which he came to the conclusion that the matter was too intricate to be the subject of exact mathematical analysis and determination. When one considers a series of steel spheres, and examines the relations of the compressed surfaces with semi-circular tracks and tries to form some clear and accurate mental picture of the phenomena incidental to the rotation of the outer race it is found impossible. I would suggest that it would be difficult to discover a more complex problem than that of a ball bearing under, say, an accelerated rotation under load. On the constructive side I put forward the suggestion that many manufacturers might help themselves greatly by presenting more accurate ideas about load capacity, for after all it *is* the load capacity for so many millions of revolutions at stated speed that counts in practical work. If we take a certain agreed standard bearing and make repeated tests of that bearing for a long period—I know that a good deal of such work has been done in this field and I suggest that it be persevered in—the results could be exchanged between one manufacturer and another, and even published in the ordinary engineering Press, so that one might by such means plot a few vital points on curves, connecting load with speed. After 20 such bearings had been tested a good idea would be obtained as to how to estimate load capacity sufficiently accurately for many commercial purposes at any practical speed required. The load tables published in makers' catalogues do not in any way overstate what the bearings listed will carry. The trouble is that in the majority of cases they understate. The author mentioned that with certain types of motor-generators he did not advocate more than one locating bearing. That is of course a point which we should fully endorse. Due to the fine clearances inherent in the ball bearings themselves it is very necessary indeed not to impose deliberately any deformations on bearing systems of more than a fraction of 1/10 000 in. at the most. This being

so when a locating ball bearing is used on a shaft, any other ball bearing on the same shaft should have a slight end-play. I feel that Mr. Parkinson has not completely stated the case when he says that he does not recommend lubrication. In fact, in his later remarks he implied that he did recommend lubrication, because evidently he is taking steps to ensure that the right lubricant is put in the bearing in the first instance and is kept there. That is what we want. In 99 per cent of the cases of returned bearings there are two reasons only why the bearings have failed. These are caused in both cases by ignorance and are (1) ill fitting by brutal methods, and (2) dirt. If one can ensure when a precision bearing is first mounted that the lubricant is clean, neutral, does not contain water, and is not subject to oxidation, and if one can further ensure that nothing gets into or escapes from the bearing housing, one can be sure that there will be no lubrication trouble with that bearing. Another speaker mentioned that he thought that a precision bearing would work quite well without lubrication. I have often heard that statement made, but many tests made in our test shops do not entirely confirm that claim. I think that a certain small amount of lubricant in roller or ball bearings performs a useful purpose. A considerable amount of rubbing takes place between ball or roller and cage, and the presence of lubricant is therefore undoubtedly helpful. When testing bearings it is sometimes found that after a certain time at a given load and speed the temperature will commence to rise, sometimes to such a point that the housing of the bearing cannot be handled. If the test be stopped at that point it will generally be found that the bearing is not damaged. Sometimes heating is attributed to the lubricant, which, having arrived at a certain temperature, begins to decompose chemically. By substituting a lubricant which is more suitable for higher temperatures we find that conditions of operation are possible which were previously believed to be impossible and which with the previous lubricant could not be maintained.

Mr. J. Speirs: Although I appreciate the work which Prof. Goodman has done, as a practical engineer I am not a convert to his suggested use of wood linings or linoleums. These may be very well in experimental work at a university but I am very doubtful if they would serve any useful purpose in general engineering, and linoleum would certainly add to the difficulty of keeping the bearings clean. One point about the load-carrying capacity that particularly interests me is the question of arriving at a formula that would enable the designer to fix the size. Such a formula would only be useful for electric machines for ordinary work and would not be reliable for all classes of motors. The nature of the load is the determining factor in load-carrying capacity and this is one of the difficulties in connection with published load tables. No published load table is of much use for any other purpose than the comparison between one size of bearing and another. While a formula that would allow a certain amount of liberty might be arrived at, I do not see the possibility for many years of this becoming a safe practice even in the electrical trade. Another feature in connection with the nature of load is the suitability of the bearing itself to resist the inaccuracy of the parts that surround it —this is very important. The firm with which I am connected—and this is borne out by my experience—came to the conclusion some years ago that there was only one bearing that was safe for ordinary standard motor work, and that had to be of the medium type. This is not because of its greater load-carrying capacity alone but because the heavier section of the race will resist to a greater extent than the light type of bearing the lack of inaccuracy in the housing. If a light type of bearing is put in a housing that is not perfectly round, the bearing will adopt the shape of its housing; this is almost bound to interfere with the life of the bearing and in some instances would produce trouble quickly. I think that Mr. Parkinson's remarks with regard to lubrication have been misunderstood. His point is that he makes no provision on his machine for the renewal of lubrication, which is entirely different from concluding that he runs the bearings dry. He means that he does not allow anyone to re-lubricate the bearings unnecessarily and, in all probability, with an entirely unsuitable lubricant. I think he has made quite a good point. I am not an advocate of running a bearing dry, as some lubrication is necessary in the interest of the cage. Bearings have been run dry, but it is not an advisable procedure. In connection with the lantern slides showing the application of various bearings to electric machines, one firm is dispensing with the use of the cage for heavy work, but experience does not show that this is perfectly sound. With regard to the question of general design, the first principle is simplicity and the absence of a multiplicity of parts and the consequent absence of errors. The future of the anti-friction bearing is undoubtedly assured and I am satisfied that this paper will do some good, but I hope that it does not immediately cause users of bearings to employ such a formula as the author suggests. To fit a roller bearing and a location bearing in the same housing at high speed is a dangerous practice and one that we have found to be unsound. High-speed bearings must be separated or else their lubrication will be difficult.

Mr. J. W. Adams: The author's remarks with regard to the selection of bearings by manufacturers as being irrational may be quite correct in principle, but in the present state of the art it is somewhat difficult, not to say impossible, for the user of the bearings to accumulate the amount of varied experience falling to the lot of the actual bearing makers. The performance of any good make of bearing and the information regarding such performance is naturally in the hands of the manufacturer, as it is hardly feasible for the user to go to the considerable expenditure of time and money in such a highly specialized branch of engineering. In my opinion the manufacturer is adopting the correct attitude, since his accumulated experience is placed freely at the disposal of the user. The author also states that he does not consider it sound engineering practice to use the maker's experience. From my own experience I would suggest that it is to be regretted that the user does not collaborate more closely with the manufacturer. Failures with both ball and roller bearings, whilst not being common when considering the great extent to which anti-friction bearings are now

used, could be considerably reduced if that collaboration were closer. Quite a number of failures are due to the wrong type of bearing being selected, and I am quite certain that many of the applications put into practice by machine manufacturers would be condemned were such applications submitted for the consideration of the bearing makers. It is, after all, quite a common thing for the wrong bearing to be selected and often incorrectly mounted. The author states that little or nothing has been published by the manufacturers of ball and roller bearings. I have made it a hobby to collect catalogues published by the various bearing makers, and I find that not only do they give interesting information but much of it is extremely useful. Referring to the question of load factor mentioned by the author, I should like to suggest that when dealing with direct-coupled motors the load factor has to be considered just as much as in a belt or chain drive. From a purely technical aspect one would merely consider the weight of the rotating mass. In practice, however, allowance must be made for any error in alignment of the equipment. It often occurs that excessive loads are imposed upon the bearings due to incorrect alignment. This trouble unfortunately happens under circumstances over which either the motor manufacturer or the maker of the bearings has no control, yet one of these is invariably blamed. The author also suggests a load factor of 4 for a belt-driven machine, but I think that it is now a generally accepted practice to estimate on a load factor of 5. He does not take into consideration the time element which, of course, is a very deciding factor in the ultimate life of the bearing. To illustrate the matter more clearly I would suggest a comparison, say, between motors for cranes which run intermittently, and a motor driving fans for the ventilation of mines, such a machine running 24 hours a day and 7 days a week for months on end. The life of the bearing depends entirely upon the fatigue of the material due to alternating stresses on the various elements. The author also gives a corresponding expression for rope drives as compared with belt-driven machines. The conditions, however, may often be more severe when dealing with a rope drive. I have now in mind particularly the textile industry. Consideration must be given to the effect of humidity, which will naturally cause the tension of the ropes to vary and consequently impose much greater loads upon the bearings. In connection with chain drives considerable allowance should be made for any overload due to stretching, resulting in links overriding the sprocket and imposing loads which are usually not allowed for in the original bearing selection. I was rather surprised to notice from a large number of lantern slides exhibited by the author that the position of the location bearing varies with different designers. In some cases the location bearing was mounted on the pinion or driving end, whilst in other cases it was mounted on the opposite end of the armature shaft. While I do not wish to suggest that it should be adopted as a standard practice, I think that the possibility of fitting the locating bearing on the driving end might be considered, as the bearing is partly located by reason of the greater radial load coming upon it, thus permitting the bearing remote from the driving end to move laterally due to any expansion or contraction of the shaft as a result of temperature variation. There must obviously be less radial load to overcome, thus allowing the bearing greater freedom to position itself correctly. The author also suggests that the selection of bearings might be in the hands of a standardization committee. While there is much to be said for this it is quite possible to carry the scheme too far as it tends to cramp design. I believe, however, that the British Electrical and Allied Manufacturers' Association are investigating the matter. If this is correct it is, I think, safe to suggest that the various bearing manufacturers will be given an opportunity of expressing their views. The reference made by the author and by several speakers in the discussion to the subject of care in the handling of bearings is very opportune. It is, I believe, now generally admitted that the makers of ball and roller bearings are working to a precision which can hardly be approximated to by those who ultimately have to mount their manufacture. It is, however, of the utmost importance to exercise every possible care when handling bearings during the process of building up the machine in which they are incorporated. I appreciate, of course, that the conditions obtaining in a workshop are totally different from those found in a laboratory or university, and after all it must be a commercial proposition. The greatest evil, in my opinion, is the utmost ignorance shown by those workpeople responsible for the actual fitting of bearings. I have seen bearings taken out of the greaseproof wrapping in which they are so carefully packed by the makers, laid on a dirty bench, possibly alongside of a vice and fitters in the process of mounting the bearing filing the armature shaft or housing, resulting in the bearing being filled with filings or other deleterious matter before it is actually put into commission. This is not uncommon, as I have found it repeatedly done in numerous workshops where ball and roller bearings are used.

Mr. R. M. Longman: A point not specially dealt with by the author is the question of lubrication, although many of the lantern slides show extraordinary precautions to prevent oil creeping along the shafts. In view of the extremely small amount of lubricant which ball bearings in particular require, the precautions shown seem to be unnecessary. It is of course essential that the right quality of grease or lubricant should be used. A case once came to my notice of a 250-kW rotary converter fitted with ball bearings; on one occasion when these were examined and cleaned a grease very similar in general appearance to the correct grease was by some mischance provided, but it had the unfortunate result of necessitating new bearings in a very short time. This sort of trouble had not occurred previously nor did it subsequently occur with the correct grease. Owing to the length of time which the correct grease will last it seems doubtful whether means for oiling should be provided, as too much oil is often as big a danger as too little, and the damage caused is generally less easy to detect. The value of the constants shown in the curves varies from 1 to 3 in different cases. It would be difficult to know what value actually to use. I agree with a previous speaker in regard to

selecting the larger bearing for the job, particularly as no heat indication of trouble occurs. It is of the utmost importance that after paying the extra price for such particularly high-class material every care should be taken in the handling and the subsequent treatment of the same, i.e. when installing and during subsequent examination.

Mr. J. G. Craven: My remarks will be from a dynamo and motor repairer's point of view. During the past six years we have had a large number of dynamos and motors sent in to us for repairs to the bearings, and I think I can safely say that 95 per cent of the faulty ball bearings were entirely due to faulty workmanship in fitting them. In some the shaft has been slack in the inner race, while in others the outer race has been slack in its housing. Probably 3 per cent of the failures are due to the use of unsuitable lubrication. I doubt very much whether 1 per cent are due to the choice of a wrong bearing. I think that in six years I can only bring to mind our having fitted two ball bearings with which there has been trouble after the machine has been repaired. In one case a manufacturer supplied us with a "tight" bearing, and I agree with the author that the bearings should be "slack" for electric motors. This case was taken up with the manufacturers, who admitted that a "tight" bearing had been supplied, because they had not the "slack" fitting in stock. It was replaced without charge. The customer did not at all appreciate the bearing running for only about six months, nor being asked to pay for taking the motor out, removing it to our works, the fitting of the new bearing—which was supplied free of charge—and the replacing of the machine in his factory. The result was that we made a concession, and carried out the work at net cost. The other instance was a pulley-end ball bearing of a 50-h.p. motor failing a few months after being renewed, due to a very badly designed belt drive, the motor being fitted with a pulley 12 in. dia. × 24 in. face, and only approximately a 6-in. shaft extension. The bending of the shaft, and the consequent strain on the ball bearing, undoubtedly caused the failure.

Prof. J. Goodman (*communicated*): The paper will, in my opinion, serve a very useful purpose in calling the attention of designers and users of ball and roller bearings to the necessity of collecting definite data on the behaviour of such bearings. Owing to the cost of ball and roller bearings the designer has to work with a much lower margin of safety than when using ordinary ring-lubricated bearings; consequently it is of considerable importance to him to know how to select the most economical bearing for his purpose. Unfortunately, however, few designers have sufficient experience or data with regard to ball and roller bearings to enable them to do so with any degree of certainty, hence they are obliged to avail themselves of the advice of manufacturers. The maker of the bearing cannot, however, possibly have the intimate knowledge of the exact conditions of working that the designer has, hence mistakes are liable to occur. To avoid such mistakes the author rightly urges designers to get data which will enable them to select their bearings from makers' lists. How are they to obtain this data? I would suggest that the Institution of Electrical Engineers should draw up suitable data forms with columns to be filled in, giving full particulars of bearings in use, together with the conditions under which they are running, and a final statement as to whether they are a success or otherwise. Such forms should be issued to designers, manufacturers, and users of ball and roller bearings, asking them for information. By this means much valuable data might be collected and afterwards tabulated, from which conclusions might be drawn. The tabulated report should be circulated amongst those who have contributed the information. In the course of a few years definite data would be available to all concerned. Ball and roller bearings have come to stay and the sooner we al know how to use them to the best advantage the better it will be for all parties concerned. The author points out that many failures of bearings are due to bad workmanship in fitting the bearings, rather than to defects in the bearings themselves. This is undoubtedly true. Even with highly skilled workmanship, failures occur due to the springing of frames, deflection of shafts and general lack of rigidity which cannot always be avoided. In view of this fruitful cause of failure I would urge that bearings should be housed with a yielding elastic backing, such as hard wood, fibre, linoleum or other suitable material around the outside of the outer ring of the bearing. Such materials allow a certain amount of "give" and act as a cushion and thereby reduce the ill-effects of vibration and shocks. I have made use of such devices in many cases with complete success, even where the manufacturers of the bearings prophesied failure. The author calls attention to the damage which may be done by shocks from improperly fitted spur gearing. I know of an instance in which some almost perfect spur gearing, ground to the nearest 1/10 000th in., was supplied by a firm of the highest standing for a very particular job, but in fixing the pinion on to the shaft it was badly damaged by rough workmanship. The foreman in charge was not much concerned and set a fitter to chip the teeth with a hammer and chisel and finish off with a file. Needless to say, the gearing and the roller bearing close at hand never worked satisfactorily. Of course the makers of the gearing and the bearing were blamed for the trouble. It does not follow that because the men who are engaged in making ball and roller bearings and who work to extraordinary degrees of accuracy are necessarily the best men to fit bearings on to shafts and into housings. The men who are accustomed to the special tools required for repetition work in making bearings are often very poor hands at doing jobs outside of their own special groove. The fitting of ball and roller bearings to their shafts and housings requires men who have had a special training in such work.

Mr. W. C. Massie (*communicated*): The author indicates that he considers it wrong for designers of electrical machinery to follow the lead of automobile designers, etc., and hand over their ball-bearing problems to specialists employed by the various manufacturers. I submit that the selection of a ball or roller bearing for a certain purpose in many cases calls for much specialized experience and is a problem very different from those which can be tackled out of hand by any engineer and, by reference to a handbook, by a mechanic. That

this is so is evidenced by the present paper which seems to contain little which cannot be found in most of the catalogues and handbooks issued by the various manufacturers. A careful study of these, together with some of the papers recently read before engineering bodies in Great Britain, will enable any engineer to select his own bearings. At the same time the judgment of a specialist based on extensive experience cannot be put into a catalogue or I can assure the author that the manufacturers would have found a way long ago. The formula given on page 784 (vol. 62) for the belt pull is very similar to but not so simple as the standard formula given in catalogues, viz.:

$$\text{Belt pull} = \frac{\text{horse-power} \times 33\,000 \times 5}{(\text{r.p.m.}) \times \pi \times \text{pulley diam. in feet}}$$

and I think that the factor 5 will be found safer than 4. The formula in this form shows that the load on the motor bearing can be varied by varying the size of pulley. This point has not been made in the paper. In the absence of information as to whether they are based on experience, calculation or estimation, Figs. 2 and 3 are of no value and it is difficult to see why an overload factor of 1·5 corresponds to an overload of 100 per cent and 1·2 to an overload of 40 per cent. I am entirely in agreement with the author that the disparity in the load figures given by various manufacturers for the same size and type of bearing is absurd. Differences in material and accuracy of manufacture may account for a small difference, but one is forced to the conclusion that some manufacturers use their load tables to advertise the superiority of their productions by suggestion. In the absence of a standard "life" basis for load figures it is certain that figures given by a manufacturer can only be used in accordance with his instructions. The question of "fatigue" and consequent "life" is being investigated very thoroughly and I do not think that it will be long before some of the manufacturers will publish "life" factors based on actual tests. Probably the late Mr. A. W. Macaulay's treatment of this part of the subject in his paper on "Endurance of Ball and Roller Bearings" read before the Institution of Automobile Engineers in 1923 is the most valuable contribution made to our knowledge of this branch of engineering for many years. On page 789 seven formulæ are given for determining the permissible combined radial and thrust load which can be taken by a radial bearing, but the author's suggestion that they are the varying views of different firms is absurd. Actually they are all correct when applied to the type of bearing to which they relate. The first is applicable to a deep-grooved single-row bearing without a filling slot, and a light type self-aligning spherical roller bearing. The fourth applies to a light type self-aligning ball bearing, and so on. The author persistently refers to self-aligning bearings without making it clear whether he means ball or roller bearings, and he nowhere mentions what is probably the best combination of bearing for heavy duty work in electrical machinery, viz. a double-row self-aligning spherical roller bearing at the located end of the shaft, and a short cylindrical roller bearing at the other end. There are few classes of engineering manufacturers who lay themselves out to supply technical information and advice as freely as ball-bearing firms, and their sole reason for wishing to have bearing problems referred to them is the desire that the bearings may be applied successfully. After all, their business depends on the successes gained. Again, it would be ridiculous for an electric motor maker to refer each motor order he received to his ball-bearing supplier, but it would be simple to plan a scheme with him so that he could tell at once if his standard bearing were capable of a given duty, or what heavier type he could fit in. There is much to commend outside technical advice when it is free and backed by guarantee. I cannot agree with the author that the importance of the use of ball and roller bearings in electrical machinery is exaggerated or that it is an open question whether it is worth while to embody them as a standard. Provided a suitable bearing is fitted it will waste less power, use less oil, last longer and will be less difficult and expensive to replace than the ring-oiled brass bearing and, last but not least, it will not "run hot." On the other hand, it may mean the making of new patterns, the calling-in of outside technical advice and the loss of revenue derived from replacement of worn-out bearings and shafts, and perhaps a little extra initial cost. The use of ball and roller bearings in motors and generators will be universal in the course of time and, I fear, before manufacturers have discovered a way to avoid the necessity of giving free technical advice.

Mr. T. D. Trees (*in reply*): I appreciate the interest shown in the paper and am pleased to note that the discussion has brought out several useful points. In some instances, however, the purpose of the paper appears to have been misunderstood. I have attempted to illustrate on suggestive lines the fact that, when selecting bearings, it is essential to make appropriate allowances for the type of drive under consideration, which is not perhaps as widely realized as it might be.

Mr. Green's remarks on excessive belt tension support my statements on page 784 and emphasize the fact that the blame does not always lie with "selection" but often with the man in the shop. However, although ring-lubricated bearings give some warning by running hot, it is probable that they suffer from as many breakdowns due to excessive belt tension as do ball bearings. I have, for example, known cases of fractured end brackets due to hot bearings of the ring-lubricated type.

Mr. Parkinson's views are very interesting, and there is much to be said for the practice of omitting lubricators or other means which make it so easy to insert any sort of oil or grease. If properly packed with the correct lubricant the motor may run without trouble for six months or longer without recharging. The lantern slides shown have simply been borrowed to give additional interest to the paper and are representative of the practice of various firms, although the designs are in some cases far too complicated in my own opinion.

In reply to Mr. Moss, it is not that I think the bearings are inclined to be on the light side generally, but rather that one may get let down in special cases, where, for instance, the bearing size is checked hurriedly or carelessly by simply taking catalogue load-tables and

applying them without any factors to suit the particular conditions. Reference to the bearing manufacturer will of course guard against such possibilities, but I suggest that the electrical manufacturer should put himself in a better position to make his own selection. With regard to the question as to the means provided for renewal of lubricant, the answer is that this is really a matter of opinion. Some firms make provision and some do not; the provision of lubricators is not so much a vital point as a selling point. No doubt the average buyer prefers to have lubricators.

Mr. Mitchell has dealt quite leniently with my paper, and I expected to have more questions to answer, since he is interested—like the two following speakers—in bearing manufacture. It is not my intention to stereotype the question of bearing sizes. He advises us, somewhat naturally, to consult the bearing maker on every occasion, and states that the calculation of load capacity is a matter of infinite difficulty. This is very true up to a certain point, and in saying this he is not unlike many of us who tell ourselves that our particular business is very complicated. However, the busy manufacturer cannot afford to let his affairs remain "very complicated," and I am confident that the up-to-date bearing maker has certain basic values for each bearing he makes, and when a customer consults him as to the size of bearing desirable for a certain duty he does not have to work from the fundamental with such complex mathematics as are implied. It is really a matter of sound business that he must have simplified methods of selection, with probably many charts, curves and load factors such as are suggested in the paper, which will enable his technical staff to give the necessary advice readily without undue time spent on each question. My proposals are that one can group the various types of loads into certain classes in order to form some opinion as to the requirements to be met, but the bearing manufacturer will no doubt have more groups than may serve our purpose. The scheme can easily be extended in many directions to suit one's individual needs. After saying that it is much better for engineers to consult the bearing manufacturers on every occasion, and after almost convincing us that we should not attempt to undertake the work of the specialist, Mr. Mitchell suggests that we can solve our own bearing problems by taking long test-runs on standard sizes. I am rather puzzled to know why he thinks that the motor maker should incur this trouble and expense and publish the results, when he would have us believe that we cannot solve such complex questions and that he has already this and much more information; yet he refrains from comment on the practical side of the paper.

Mr. Spiers voices the policy adopted by his firm in stating that published load-tables are of little value except for comparison; they prefer to be consulted by the user and therefore do not give load-tables except for the small sizes of bearings. He suggests that it is unwise to use the formulæ put forward, but I am sorry that he gives no other information in this respect. He appears to think that I would avoid collaboration, instead of which I suggest that it is not necessary to have such close collaboration as is essential when no load-tables or factors are published. It is not intended that the formulæ should be used without regard to the nature of the load, but with such a method of comparison the ordinary problems may be solved; when the question is of peculiar difficulty one should consult the manufacturer, but one does not want to be sending him inquiries every day. It is very interesting to hear that light-type bearings conform to the shape of the housing. Although I have thought that the races might offer some approach to the shape of inaccurate housings, I did not think that it was quite so rapid a process as Mr. Spiers tells us. In this connection it may be useful to remark that in cases where a split bearing-bracket is required, the practice I have generally recommended and used is to fit the ball or roller bearing in a separate solid housing in order to prevent the outer race being clamped injuriously when bolting the bracket together. When one is using large bearings of the heavy type this may be unnecessary if care is taken when machining the housing and assembling, but it is always safe practice. I agree with Mr. Spiers in his remarks on lubrication, in his reference to the omission of cages in certain heavy applications and the numerous parts shown in other applications, as illustrated in some of the lantern slides. It is also agreed that high-speed location and journal bearings should be separated.

Mr. Adams says that it is difficult for users to accumulate experience and he regrets that the user does not collaborate more closely. It is, however, not so difficult to accumulate experience. He wants to have every question raised with the bearing maker, but, as already pointed out, it is considered unnecessary to waste days in correspondence when one might settle most questions in an hour. I am afraid that he has read the paper hurriedly or he would have noticed that the questions of incorrect alignment and the life of the bearings are both dealt with. Further, he is quite in error in supposing that I favour the selection of bearings being in the hands of a Standardization Committee; it is definitely stated on page 790 that I consider this to be most undesirable. Also, he has misquoted me in another place "that it is unsound practice to use the maker's experience." My contention is that it is unsound practice to hand over the whole business of selection to the maker and be content to remain in ignorance as to whether the bearings are ample or not, without being able to check their capacity when required. With reference to catalogue collecting, this has also been a hobby of mine, and it is very easy to prove by reference to those issued up to the date of writing the paper that British makers publish little or nothing on allowances or "load factors." What information is given in this direction is Continental in origin and is not found except in the publications of those whose policy is the result of some control from the same source. It is agreed, however, that since they commenced business in this country the firm represented by Mr. Adams have published more data than is usual in British practice. He makes a useful point regarding the effect of humidity on rope drives; this should not be lost sight of, but I suggest that my load factor will allow for this in general cases. The chief difficulty may occur when an operator deliberately wets the ropes in order

to get a tighter drive, which is sometimes done. My own preference regarding location and thrust bearings is to mount them at the end remote from the drive in most horizontal machines; by so doing, the shaft between the drive and the actual rotor can be shorter and stiffer, and in the case where a journal bearing also serves as a locating bearing it seems better to put the additional thrust load on to the one carrying the lighter journal load.

In reply to Mr. Longman, the question of lubrication was considered to be outside the scope of the present paper. Much could be written on this side of the subject, but it is preferred not to go into the matter at the moment except to say that the grease or oil used should be chemically neutral. There are various products marketed for this special purpose. I do not understand his difficulty in regard to the constants varying in certain cases; it seems logical enough to me that they should so vary, according to the speed of the gearing and the materials used, for the reasons I have given in the paper.

Prof. Goodman has carried out a considerable amount of research work and is a recognized authority on ball and roller bearings, therefore his remarks are very interesting and much appreciated, but I must confess to serious misgivings as to the value of his suggested data forms. I feel that it is infinitely preferable to encourage the engineer to select for his own particular needs, with the assistance of the bearing maker if necessary, than to attempt what might be termed a national movement, which would be very slow in operation and unwieldy in its collected data because of the wide range of loads, types and sizes as mentioned in the paper. This idea would institute a basis of averages, rather than a basis of design values. If the average practice in the country is too good, good, or poor, then his collected data will be also too good, good, or poor, as the case may be; and who can determine the best practice for individual needs except by personal experience after all? With regard to his suggestion of elastic backings, I am, like Mr. Spiers, unconverted. In the laboratory such methods may be used, perhaps; but in practice, particularly in electrical machines, I am sure that they would be a fruitful source of trouble. It should be quite sufficient to imagine the result of fitting a yielding bearing housing in the case of motors with small air-gaps. If one is dealing with excessive vibratory or shock loads, then the better way is to interpose some flexibility between the drive and the bearing, and not between the bearing and the housing. Sometimes this can be done by introducing a flexible coupling, or by using non-metallic pinions; but, whatever else may be necessary, I do not agree that we should depart from the solid housing for electrical machines.

Much of Mr. Massie's criticism has already been replied to in the discussion. The curves are based on my own experience, and the apparent inconsistency of the factors for momentary overload in Fig. 3 is explained by the following: A bearing should be able to withstand a certain momentary overload and one need not fit a bearing capable of *continuously* dealing with this maximum momentary load. An electric motor is also capable of withstanding momentary overloads up to a certain value according to its design. If the estimated momentary bearing overload is small it is quite probable that the motor will respond to larger demands than that, should the drive require it; and, conversely, if the estimated bearing overload is large it is probable that the motor will not exceed this output. Hence it is that I use a smaller margin between the factor and the overload on the small values than on the higher momentary loads. I am sorry that I have not made it sufficiently clear that by self-aligning bearings is meant ball bearings. In the paper originally submitted the various types were explained, but this was omitted later. The self-aligning roller bearings to which Mr. Massie refers are of comparatively recent date and are not much required except for really large machines and heavy service. He may not agree that ring-lubricated versus ball and roller bearings is an open question, but it is a fact that several of the leading motor makers prefer to use ring-lubricated bearings, and others are sitting on the fence without conviction either way. The saving in power by the adoption of ball or roller bearings in electrical machines has little relative importance. The loss in bearing friction is very small compared with iron, copper and other losses, and even if one could have really frictionless bearings the motor would gain little in efficiency. Also, in starting up a motor the energy required after the first few revolutions will be practically the same for either type of bearing, because it is chiefly expended in accelerating the masses, and not so much in bearing friction.

In conclusion I should like to thank The Hoffmann Manufacturing Co., Ltd., The Skefko Ball Bearing Co., Ltd., Messrs. Ransome and Marles Bearing Co., Ltd., and Messrs. Rudge-Whitworth, Ltd., for the loan of samples and lantern slides, and for the attendance of their representatives whose contributions to the discussion are greatly appreciated.

DISCUSSION ON "IRON LOSSES IN D.C. MACHINES." *

SCOTTISH CENTRE, AT EDINBURGH, 10 MARCH, 1925.

Mr. W. B. Hird : Designers are always interested in any new investigations or methods of calculation which increase their scientific knowledge of what is actually going on in a machine and which improve the methods whereby they predetermine a machine's characteristics. There are doubtless many cases in which the use of elaborate formulæ and the application of all the refinements that fresh knowledge puts at their disposal are justified. It must nevertheless be conceded that for the ordinary everyday work of a design office the great desideratum is simple formulæ the application of which does not involve long and tedious calculations and which can be relied on to a fair degree of approximation, rather than a more elaborate method which strives for a quite unnecessary degree of accuracy. I therefore welcome the author's view that it is better to use a formula giving both the eddy-current and hysteresis losses than to use a separate formula for each, even though it is true that the single formula cannot be justified from theoretical considerations. The art of the designer consists in judging within what limits these approximate formulæ may be used and at what point more elaborate methods are necessary. As a matter of fact I have for many years used with satisfactory results a formula much on the lines of that given by the author, but with modified constants. The machines on which the author carried out his experiments were somewhat small. This is almost necessary in experimental work of this sort, because big machines are very seldom available. Consistency in the results obtained with four different machines is, however, to be expected when the machines are more or less similar in size and construction, and there may be danger in expecting the results thus obtained to hold true for machines of a totally different type or size. I do not agree with the author's explanation of what happens under the commutating poles. Since any interpole is of the same polarity as one or the other of the neighbouring main poles, it cannot be right to consider the losses as due to a double reversal (one under the interpole and one under the main pole), and at the most the losses due to the presence of the interpoles can only be due to a depression in the curve of field strength between the two poles of similar polarity —not to a total reversal such as the author claims. The formula generally used in textbooks gives 1·6 as the index for hysteresis and 2·0 for eddy currents. The values obtained by the author vary from 1·6 upwards for hysteresis and from 2·0 upwards for eddy currents, the maximum in each case being about 20 per cent in excess of these figures. That difference is no doubt important from the purely scientific point of view, but I do not think that it is very important in practice. An addition of even 10 per cent to the core losses of a dynamo—these core losses being only 20 per cent of the total losses to begin with—does not make any very considerable difference in the final results.

Mr. J. C. Macfarlane : I congratulate the author on his method of extending the proposals* made by Mr. Burge and myself in 1908 to cover load conditions. These proposals applied only to the line of similarly designed machines which we were discussing at that time. I agree that expressions of the type included in the present paper can be made to give sufficiently accurate estimates of the iron loss, even under load conditions, in machines of similar design and construction, but I cannot agree that either the constant or frequency index proposed by the author can be of universal application. Both values depend on such variables as (*a*) the ratio (air-gap length)/(slot-opening), (*b*) the construction and shape of the pole-shoes, and (*c*) the air-gap density. By paying careful attention to these variables, machines have been constructed (with lohys iron stampings 0·018 in. thick in the armature core) having measured light-load iron losses less than two-thirds of those calculated with the author's constants, and for the machines in question the frequency index is not greater than 1·37. The iron loss actually taking place in, or due to, the pole-shoes is, even in modern machines, a considerable part of the whole. The total light-load iron loss can easily be increased by 20 per cent by boring out the pole-shoes alone, particularly if the air-gap still remains small, and an increase of 50 per cent is not unusual if the armature core surface is machined. The paper will be very useful to designers, and expressions of the type with suitable constants can easily be obtained for the designs of machines in which they are interested.

Dr. S. Parker Smith : While some of the facts in the paper are not new to designers, it is a great advantage to have the question of high losses in the iron emphasized as much as possible and also to insist that a great part of this loss is avoidable. Taking the figures on page 48, for example, it is seen that the actual loss was found to be four times the loss given by the makers. Fig. 17 might well be used by some makers, who take no care to reduce iron losses. From time to time during the past 20 or 30 years attention has been drawn to the excessive iron losses in all classes of electrical machinery. Even when due allowance has been made for all unavoidable additional loss in the end plates and other constructional parts of the armature and for all additional losses due to rotating hysteresis, the fact remains that in very many machines at present built the iron loss is at least twice as great as it need be. The causes of this avoidable additional loss are mainly bad workshop methods, such as punching the slots with badly set or blunt dies, filing and drifting the slots after the

* Paper by Mr. E. Hughes (see page 35).

* *Journal I.E.E.*, 1909, vol. 42, p. 232.

core, has been assembled, carelessness or neglect in removing the bad edges from the stampings. Not only in small machines such as those with which the author deals, but also in transformers and turbo-alternators, the iron losses may well be halved by careful workmanship and constructional methods. Mention might be made also of the eddy-current losses which may occur in the armature copper, even when the machine is unloaded. The author is to be thanked for again drawing attention to this important matter and it is to be hoped that his paper will induce some firms to pay more heed to the careful construction of their cores. The repairer also is often to blame in this connection because of his readiness to use the file and drift when replacing coils.

Dr. A. E. Clayton (*communicated*) : The predetermination of the value of the iron losses is naturally a matter of considerable importance to designers of electrical machinery. As stated by the author, the problem is complicated with toothed armatures owing to the fact that the magnetization is neither purely alternating nor purely rotating. It is further complicated owing to the effect of filing, etc., in the slots upon the insulation resistance between core plates; in addition there may be appreciable losses in the core end-plates and in the pole-shoes. It is well realized that the losses occurring with such machines are very much greater than those in the case of transformers working under similar conditions, so far as maximum flux density and frequency are concerned, but the exact reasons for the great discrepancy are not in every case fully appreciated. So far as the teeth are concerned, the magnetization may, for all practical purposes, be taken to be purely alternating. But—and this is most important—the flux does not change according to a sine law, following instead the wave-shape represented by the flux-distribution curve. This has a most marked effect upon the value of the eddy-current losses. Moreover, as regards the teeth, any burring over of the plates, due to filing, will have a pronounced effect. As regards the core, both the intensity and direction of magnetization change, and the effect set up may be called elliptical rotating magnetization. The actual shape of the air-gap flux distribution curve will have but a minor effect upon the core losses, and, in addition, filing out the slots will only slightly influence the value of the eddy-current losses. It follows, then, that to calculate separately the iron losses in the teeth and in the core, formulæ should be used in which the loss constant used for the teeth differs from that used for the core. Since the conditions of magnetization are so widely different, a single value for the constant cannot be expected to give correctly both the tooth loss and the core loss. However, in practice, where the machines all have much the same proportions, the aggregate losses as deduced from a single formula of the type given on page 47 are generally sufficiently near to the test figure. But when such a formula is applied to abnormal machines, such as those in which the core is either abnormally shallow or abnormally deep, the results obtained are very often unsatisfactory. In calculating iron losses in rotating machinery, then, in my opinion, it is desirable to adopt a value for the loss constant for the teeth different from that used for the core. The need for doing this was made very apparent to me some considerable time ago when investigating the discrepancy that existed between the calculated and measured iron losses on a large number of turbo-alternators. I found that whereas the measured losses for 2-pole machines were invariably much less than the calculated figure, those for 4-pole machines were greater than calculated. The ratio (tooth volume/core volume) being much smaller for the 2-pole than for the 4-pole machines, indicated the probability that the tooth losses were under-estimated and the core losses over-estimated. It was then not a difficult matter to determine, for the teeth and core respectively, values for the core-loss constants which gave in all cases a reasonable agreement between calculated and measured figures. On page 45 the author discusses the effect of the wave-shape of the flux-distribution curve upon the eddy losses in the teeth. It appears to me that the value of the eddy losses in the teeth is completely determined by considering solely the manner in which the flux changes in them. When a coil is moved past the pole of a magnet the effect is to cause a change in the flux linked with the coil, this change corresponding exactly to the net rate at which the coil-sides cut through the magnetic field. The E.M.F. established may be regarded as being due either to the coil-sides cutting through the field or to the rate of change in the flux linked with the coil. In every case the rate at which the flux changes in a circuit—quite independent of the manner in which the change is brought about—determines entirely the value of the E.M.F. induced. It does not appear, therefore, that the losses given in Equation (1) will occur in addition to those corresponding to Equation (2). The wave-shape of the flux-distribution curve has undoubtedly an important bearing upon the magnitude of the eddy-current losses in the teeth. Moreover, contrary to the view that appears to be very generally held, the maximum value of the flux density is by no means the all-important criterion, but it is of the utmost importance that the flux shall not change too rapidly. When the flux linked with a circuit changes by an amount Φ, the quantity of electricity which will circulate in the circuit is Φ/r, a value quite independent of the time taken for the change in the flux. The E.M.F. developed is, however, determined by the rate at which the flux changes. The energy produced is determined by the product of the mean E.M.F. developed and the total quantity of electricity circulated, and thus increases in proportion to the rate at which the flux changes. Applied to the case of eddy currents in the teeth, it may then be taken that the quantity of electricity circulated in the eddies is determined directly by the maximum flux density, but that the energy developed is determined by the product of the quantity of electricity circulated and the rate at which the flux changes. It is then the shape of the flux-distribution curve at the pole fringe that is of major importance. This may be illustrated for the case of the two simple rectilinear flux-distribution curves indicated in Figs. A and B, the maximum flux density being the same for the two cases. Fig. A roughly corresponds to the case of an unsaturated

turbo-alternator, and Fig. B is a very rough approximation to the case of a d.c. machine. For a very narrow tooth, the time taken for the flux to change from maximum to zero will correspond to the motion of the armature through 33·3 per cent of the pole-pitch for case A and only 7·5 per cent for case B. The eddy losses for case B are therefore relatively 33·3/7·5 (= 4·4) times as great as for case A. This simple calculation, whilst not taking account of all the factors, is sufficiently exact to illustrate the great importance of the actual flux-distribution curve, and the desirability of employing pole-shoes of a suitable shape.

Mr. E. Hughes (*in reply*): It is not stated in the paper that the commutating poles give rise to a double reversal of the flux as suggested by Mr. Hird. The depression in the flux curve between two poles of the same polarity is, however, so great that the flux density in a tooth midway between two such poles is very low.* It has to be borne in mind that the commutating pole is always adjacent to the weakened tip of the main pole of the same polarity; and the depression in the flux wave is thereby accentuated.

Whatever the relationship of the iron losses to the total losses, there is no question about their importance in determining the temperature-rise of the armature; and every endeavour should be made to reduce them as much as is practicable. It is therefore interesting to learn that Mr. Macfarlane has been able to effect a reduction of about 30 per cent by careful attention to various factors.

It will be readily granted that constants determined from comparatively small machines may not be universally applicable; but the main purpose of the paper has been to deal with methods rather than with numerical constants. The suggestion of Dr. Clayton concerning the separation of the tooth and core losses is a partial solution of the problem—but it is far from being a complete one. There is first the difficulty of separating these losses, and then there is the difficulty of determining the flux distribution in the core—a distribution that depends upon the pole-pitch, core depth, flux density, etc. Such a method would result in arbitrary constants which would not be of universal application.

In his discussion of the eddy losses in Figs. A and B, Dr. Clayton has overlooked the difference between the eddies in the teeth due to rotation and those due to transformer action. He states that when a coil is rotated through a magnetic field "the E.M.F. established may be regarded as being due either to the coil-sides cutting through the field, or to the rate of change in the flux linked with the coil." The first method was used in deriving Equation (1) on page 45 of the paper, whilst Dr. Clayton in proceeding to demonstrate the application of the second method has discussed an entirely different loss. If a loop be rotated in the magnetic fields represented by Figs. A and B respectively, the change of flux linkages per cm of axial length during the sixth of a cycle taken by a coil-side to move

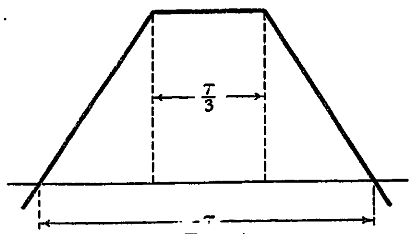

FIG. A.

from position of zero field to that of maximum density, say B, in Fig. A is $\frac{1}{3}B\tau$. If f be the frequency, the corresponding rate of change of flux linkages is $\frac{1}{3}B\tau \div (1/6f)$, i.e. $2B\tau f$. Hence the energy lost during this interval is proportional to $2B\tau f \times \frac{1}{3}B\tau$. For Fig. B, the corresponding change of flux linkages is $B \times 0 \cdot 075\tau$ in $0 \cdot 0375/f$ seconds, so that the rate of change of flux linkages is again $2B\tau f$; and the energy lost is proportional to $2B\tau f \times 0 \cdot 075B\tau$. Consequently

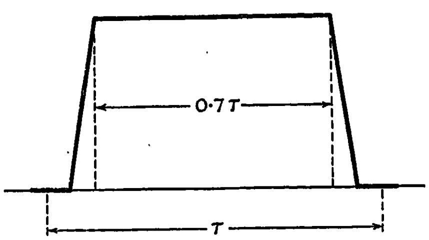

FIG. B.

the ratio of the eddy losses of Figs. A and B during the interval taken by a coil-side to pass from zero to maximum field strength is $0 \cdot 667/0 \cdot 15$, i.e. 4·45. On the other hand, when the eddy currents due to transformer action in the teeth are considered—the paths of these currents being at right angles to those of the eddies set up by rotation—the value of 1/4·4 derived by Dr. Clayton is obtained for the ratio of these eddy losses for Figs. A and B. These results show that it is essential to consider quite separately the eddy losses due to rotation and to transformer action; and this is the purpose of Equations (1) and (2) on page 45 of the paper.

* C. C. HAWKINS: "The Dynamo," vol. 2, 6th ed., p. 47.

DISCUSSION ON "THE USE OF SINGLE-CORE LEAD-COVERED AND ARMOURED CABLES FOR ALTERNATING CURRENTS." *

Mr. B. S. Hornby (*communicated*): I have read with interest the results of the tests described in the paper by Messrs. Harvey and Busby (see pages 368–378) and also the conclusions reached by Prof. Cramp (pages 379–383). The losses predicted in the case of extra-high-tension cables by Prof. Cramp are lower than one would anticipate, and I suggest that they should be confirmed by similar tests made on long lengths of cable laid underground. These tests could be carried out by bunching the three cores of existing

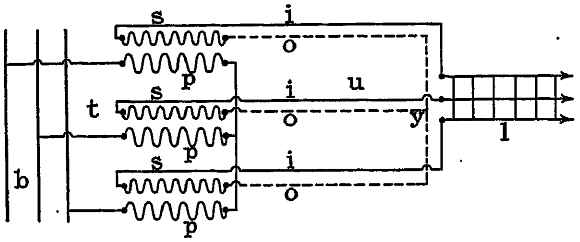

FIG. A.

e.h.t. duplicate mains, and, as the results would be of considerable practical value, no doubt a supply undertaking would allow their mains to be used for such tests at times of light load, when they could temporarily dispense with such mains. Similar tests made on cables protected by double steel-tape armour would also be of interest. I have also considered the problem of transmitting three-phase current through separate cables for each phase, but have worked on it in another direction, namely, by the use of a lightly-insulated

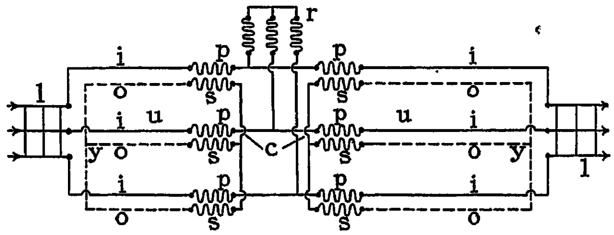

FIG. B.

outer concentric conductor arranged to carry a current equal to but opposite in direction to that in the main inner conductor. This arrangement eliminates all hysteresis and eddy-current losses in the armour and sheath, but doubles the copper loss. This loss is, however, of no serious consequence when the power is transmitted the greater part of the distance by overhead wires. The equalizing current is obtained by (1) moving the star-points at the transmitting and receiving ends to the cable ends, and (2) the use of current transformers on intermediate lengths of underground cable as shown in Figs. A and B, in which "i" and "o" indicate the inner and outer conductors of the concentric cables "u"; "p" and "s" the primary and secondary windings of the step-up or step-down transformers "t" or current transformers "c"; "l" the overhead lines; "y" the star-points; and "b" the busbars at the transmitting station.

* Paper by Prof. W. Cramp (see page 379).

Mr. D. M. Simons (*communicated*): I have been interested in the two recent cable papers by Prof. Cramp, the first by him and Miss Calderwood on single-core lead-covered cables, and the present paper covering in addition the effects of armour. Prof. Cramp's work should be of great interest to all cable engineers, and I think that his calculations of the open-circuit loss in the sheaths of cables and his work on armoured cables should be of particular importance. When the former paper first appeared, I noted that the author's formula for the simplest case of all, the case of short-circuited sheaths, to which he undoubtedly gave less consideration than to the other more difficult cases, was not in agreement with the work of other investigators. Considering the case of a single-phase circuit of two parallel single-core lead-covered cables, the distance between whose axes is D and the mean radius of whose sheaths is r, Prof. Cramp takes $K = r/D$. His formulæ contain the term $\log[(1 - K)/K]$, while, using the same symbols, most other writers have a term $\log(1/K)$. The difference between the two terms is fundamentally a difference in limits of integration; Prof. Cramp integrates the flux out of the sheath of the distant cable, while the more usual method is to integrate to its centre or axis. I myself believe that the integration should probably be carried to the axis of the second cable, as is done in the calculation of the inductance of parallel wires, for reasons so clearly stated by Nesbit.* In particular, Fisher,† Atkinson,‡ Clark and Shanklin,§ Capdeville,|| Sacchetto,¶ and Melsom and Beer ** all agree in effect upon the use of the term $\log(1/K)$. I rather hesitate to raise the question, in view of my appreciation of the value of these two papers, but the matter is one of practical importance, since the difference between the two formulæ is by no means negligible. Dwight,†† in his article on this subject, in which he developed practically a rigid formula for the sheath-circuit eddy loss which takes into consideration the proximity effect and holds even if the sheaths are tangent, mentions the earlier paper by Prof. Cramp and Miss Calderwood and calculates that the sheath loss is 37 per cent of the conductor loss instead of the 16 per cent given by them in one of the tables, the entire

* *Electric Journal*, 1919, vol. 16, p. 284.
† *Transactions of the American Institute of Electrical Engineers*, 1909, vol. 28 p. 747.
‡ *Ibid.*, 1912, vol. 31, p. 804.
§ *Ibid.*, 1919, vol. 38, p. 917.
|| *Revue Générale de l'Électricité*, 1920, vol. 8, p. 171.
¶ *L'Elettrotecnica*, 1922, vol. 9, p. 667.
** *Journal I.E.E.*, 1925, vol. 63, p. 190.
†† *Electric Journal*, 1924, vol. 21, p. 62.

difference being in the logarithmic term. When, however, the same term was included in the present paper also, it seemed to me that the point should be settled one way or the other in the interest of all cable engineers. In view of the general agreement on one form of equation and, in particular, of Dwight's direct statement in regard to this term, I should like to ask Prof. Cramp his reason for using his form of the logarithmic term, or if there is any way of reconciling the two points of view. All the various formulæ should undoubtedly give approximately the same numerical answer, in order that the calculated value of induced sheath loss may not be a variable depending upon which particular formula is used.

Prof. W. Cramp (*in reply*): I do not think that there is any reason to suppose that long lengths of cable laid underground would give results substantially different from those upon which my analysis has been based. Everything depends, of course, upon the dimensions of the cable and the armouring, and if I could find a municipality willing to place some long lengths at my disposal, as suggested by Mr. Hornby, I should certainly be willing to take a confirmatory test. The difficulties, however, are considerable. The distribution of the magnetic field about three cores in parallel is not the same as about one central core, and the losses will certainly be greater in the former case. It is also difficult to get underground cables upon whose spacing and straightness reliability can be placed. Tests on double steel-tape armour are not, in my opinion, of much value, as such cables are generally avoided. Mr. Hornby's system of avoiding losses by moving the star-point of the system is very interesting, but, I think, would only be adopted for comparatively short lengths; indeed, the object of his device seems to be to connect short breaks in long overhead lines. For considerable distances the extra expense of the sheath copper, and the extra loss entailed, render the use of his system doubtful.

I fully expected that the question raised by Mr. Simons would occur in connection with the term $\log[(1 - K)/K]$, and it was with this expectation that I carefully guarded myself by inserting the last paragraph on page 481 of Volume 61 of the *Journal*. The difference between the above expression and the usual term $\log(1/K)$ is, as Mr. Simons points out, introduced by the limits of integration. Now there is no doubt that where the circuit consists of a pair of small parallel cylinders the limits adopted by the writers quoted by Mr. Simons are correct, but where these cylinders are enclosed in other conducting cylinders, of much larger diameter and forming no part of the original circuit, the case is, I think, quite different. For, under the former conditions, any magnetizing force arising from cylinder A and passing beyond the centre of cylinder B is exactly counteracted by an equal force due to cylinder B. This is the fundamental reason underlying the limits usually adopted, which are commonly used for the inductance of a pair of parallel wires. We are not here concerned, however, with the inductance of the original cores, but only with the induced currents in the sheaths that surround them, which are themselves low-resistance conductors. It is clear, therefore, that while there will be between the sheaths an uninterrupted path for the magnetic flux, the mere presence of a portion of either sheath will tend to deflect or damp out any alternating flux beyond this region by reason of the eddy currents induced in the portion of the sheath that intercepts the flux. The effect, then, of the presence of the sheath will be to increase the density between the sheaths slightly, and to reduce very effectually any magnetic flux that would otherwise exist between the sheath and the core of the conductor B due to the current in conductor A. I hope that this will explain to Mr. Simons why I have adopted the limits which he questions, and also why I inserted the paragraph on page 481 referred to above.

CHARTS FOR REGULATION OF TRANSFORMERS.*

By ARTHUR A. BOELSTERLI, Associate Member.

(*Paper first received 20th October, 1924, and in final form 31st January, 1925.*)

SUMMARY.

To ascertain the regulation—an essential characteristic of a transformer—when the ohmic and reactive drops respectively are given involves a good deal of calculation.

In the first part of the paper, charts are presented, from which the results can easily be read.

In the seond part a simple "chord diagram" is developed, which is well suited for approximate estimates.

Both methods are based upon the formula recommended by the American Institute of Electrical Engineers and permit a clear visualization of the relations implied.

1. REGULATION CHART.

In clause 6053 of the "Standards of the American Institute of Electrical Engineers" the regulation of a constant-potential transformer is defined as the difference between the no-load and rated-load values of the secondary terminal voltage at the specified power factor, such difference being expressed as a percentage of the rated-load secondary voltage.

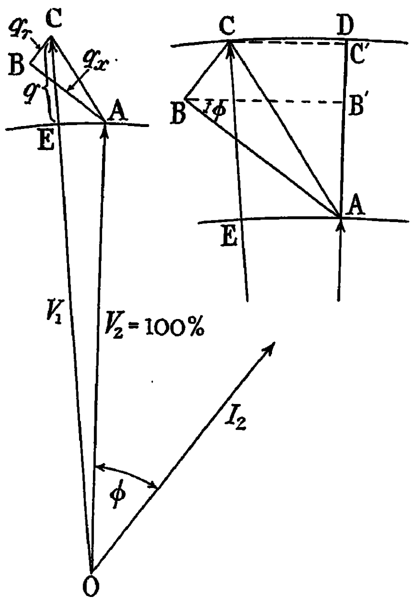

FIG. 1.

Fig. 1 represents the vector diagram, under load conditions, with the ohmic and reactive drops not separated into primary and secondary portions, but considered as total drops for the transformer. In making the vector of the secondary terminal voltage equal to 100 units of length, regulation as defined above is directly represented in the diagram. Although this paper specifically deals with transformers, attention is called to the fact that in the above form the diagram of vectors is identical with the diagram of a transmission line when electrostatic capacity is neglected and assuming concentrated resistance and inductance. Hence the methods developed below are equally applicable to a transmission line.

Reverting to the case of the transformer, it is assumed that either by tests or by computation from design data the ohmic and reactive drops are available. Thus the task is confined to the determination of the regulation from the configuration of vectors as shown in Fig. 1.

Regulation figures are usually required for several power factors. Various methods have in the course of time been developed for readily obtaining these figures. Among the graphical solutions the diagram of Kapp is well known. The Mershon diagram, which is merely an ingenious generalization of the diagram shown in Fig. 1, although applied almost exclusively to transmission lines, lends itself to the case of the transformer. Both methods mentioned, however, possess, owing to the relative smallness of the voltage-drops, the disadvantage of requiring to be drawn to a large scale in order to obtain results of acceptable accuracy. Analysis of the vector diagram, on the other hand, yields varied expressions for the determination of regulation. In its specific recommendation the American Institute has been fortunate in selecting a formula of excellent practical value (see clause 6391 of the Standards). It is this formula which is here made the basis of a novel graphical representation on the alignment principle. The charts developed afford a means of rapidly ascertaining regulation and it is hoped will be found useful, especially for routine work.

A second graphical solution of the formula will subsequently be shown in the shape of a simple circle diagram, which is thus well suited to the needs of those who but occasionally encounter the problem.

Let q_r = percentage ohmic drop;
q_x = percentage reactive drop;
$m = \cos\phi$ = power factor;
$n = \sin\phi$ = reactive factor;
q' = percentage regulation, uncorrected;
q = percentage regulation, corrected.

The formula referred to can be written as follows:

$$q = q' + \delta \quad . \quad . \quad . \quad . \quad (1)$$

where
$$q' = mq_r + nq_x \quad . \quad . \quad . \quad (2)$$

and
$$\delta = \frac{(mq_x - nq_r)^2}{200} \quad . \quad . \quad . \quad (3)$$

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

The quantity denoted by Equation (2) is evidently represented by AD in Fig. 2 and thus constitutes a first approximation. δ is a correction term, which, added to q', marks a near approach towards the true value. In Fig. 2, δ is represented by AD. Equation (3) is easily derived from the diagram with the aid of an expansion, omitting terms of higher order. The accuracy attained is such as to bring the theoretical error within the limits of the errors of measurements.*

Equations (2) and (3) contain the same four variables (m and n obviously count only as one, as they are merely the cosine and sine of the same quantity). Owing to their construction both formulæ lend themselves to development into alignment charts. Equation (2) is developed in Fig. 3. Here all the divisions on vertical lines are uniform. This makes the plotting of the chart extremely simple. The procedure on an empirical basis can be summarized as follows: Lay off arbitrarily two uniformly graduated scales for q_r and q_x; calculate from Equation (2) for each power factor to be represented in the chart two or (better) three pairs of values of q_r and q_x corresponding to one and the same value of q.

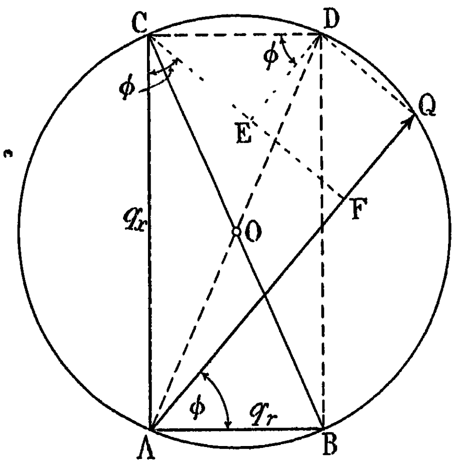

FIG. 2.

The straight lines joining corresponding values of q_r and q_x then intersect in points through which the respective power-factor lines can be drawn parallel to the q_r and q_x scales. Moreover, the unit of gradation is for any power-factor line the $1/q$th part of the distance of the aforementioned point of intersection from the zero point on that power-factor line. The zero points are all on the line joining the zero points of the q_r and q_x axes. By connecting the points on the scales that correspond to equal values of q the curves of constant regulation are obtained.

Fig. 4 represents Equation (3). The vertical gradations are here far from uniform and are obtained by methods for which the reader must be referred to textbooks on Nomography.

It will be noted that both Figs. 3 and 4 are arranged for lagging power factor only, in accordance with Equations (2) and (3), which hold good for lagging power factor only. The range of this formula can, however, be extended to cover the case of leading power factor by attributing in this case the negative sign to the reactive factor, and changing the signs accordingly. Similar charts to those presented could be drawn for the new conditions.

* See P. G. AGNEW and F. B. SILSBEE: "Accuracy of the Formulas for the Ratio, Regulation and Phase Angle of Transformers." Scientific Papers, Bureau of Standards, S. 211.

The use of the charts shown in Figs. 3 and 4 is best understood from a few typical examples.

Example 1.—For a transformer of 3 600 kVA the copper losses are given as 32 400 watts and the reactance as 8·5 per cent; it is required to determine the regulation figures for power factors of 1·0, 0·9, 0·8, and 0·7.

The ohmic drop q_r is in general obtained by dividing the copper losses in watts by 10 times the kVA output. In the above case this results in $q_r = 0\cdot90$ per cent. q_x is directly given as 8·5 per cent. Marking these values on the respective scales in Fig. 3 and laying a straight-edge across, we read the following figures for the regulation, representing a first approximation:

Power factor ..	1·0	0·9	0·8	0·7
Regulation.. ..	0·90 %	4·50 %	5·80 %	6·70 %

From Fig. 4 we read by the same procedure:

Correction	0·36 %	0·27 %	0·20 %	0·15 %

The correction always being directly additive, we obtain by addition the exact figures for regulation as follows:

Power factor ..	1·0	0·9	0·8	0·7
Regulation.. ..	1·25 %	4·75 %	6·0 %	6·85 %

The figures are rounded off to one-twentieth of 1 per cent, which corresponds approximately to the accuracy the charts afford.

Example 2.—From measurements on a transformer in operation the following figures on regulation are known:

Regulation at 0·85 power factor .. .. 4·5 %
,, at 75 % load and 0·70 power factor 4·1 %

What are the percentage copper losses and the reactance of the transformer?

This is the converse of the problem in Example (1). It is first necessary to refer the second regulation figure to full load, assuming proportionality between load and regulation. We thus obtain the regulation at 0·70 power factor to be 5·5 per cent. Plotting now in the regulation chart the two points corresponding to the two pairs of values of power factor and regulation, and laying a straight-edge through them, we read on the q_r and q_x axes:

$$q_r = 1\cdot26; \quad q_x = 6\cdot5.$$

q_r is approximately equal to the percentage copper loss; q_x is the reactance in the first approximation. It is now possible to obtain from the chart correction terms corresponding to the regulation figures given. Deducting these and using the corrected values again in the regulation chart we obtain figures of greater accuracy. For $q_r = 1\cdot26$ and $q_x = 6\cdot5$ we read the corrections:—

Power factor	0·85	0·70
Correction	0·12 %	0·07 %
The latter figures deducted from ..	4·5 %	5·5 %
Give	4·28 %	5·43 %

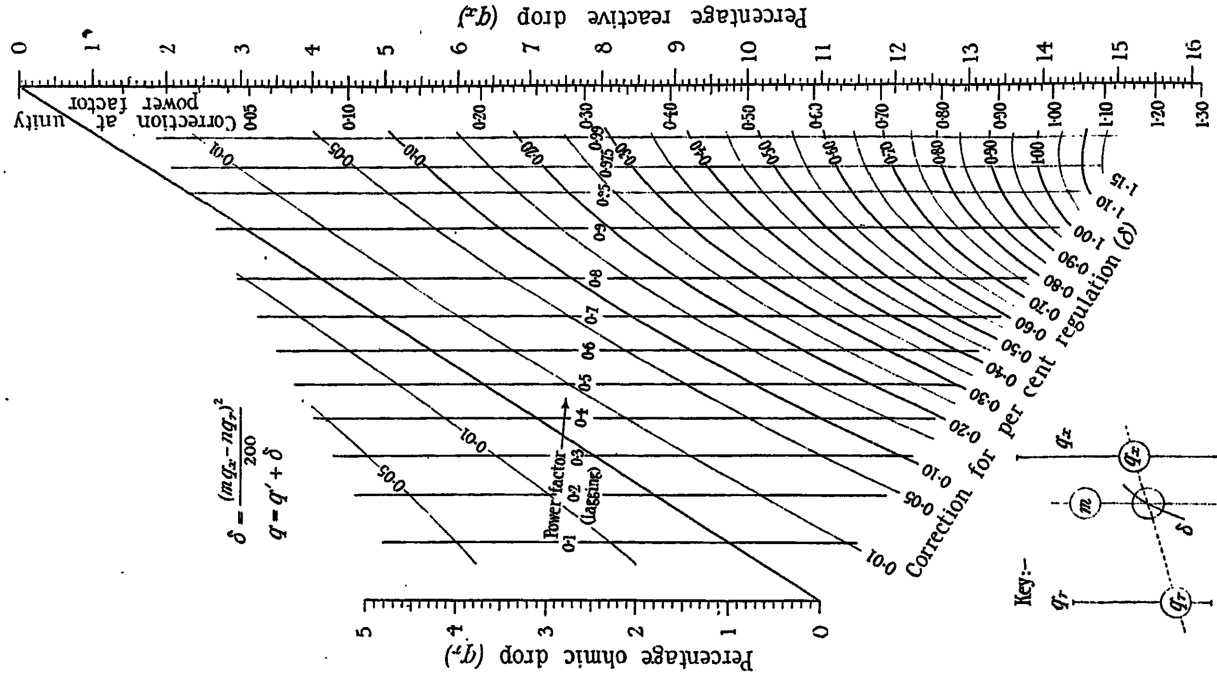

FIG. 4.—Chart for determination of correction term.

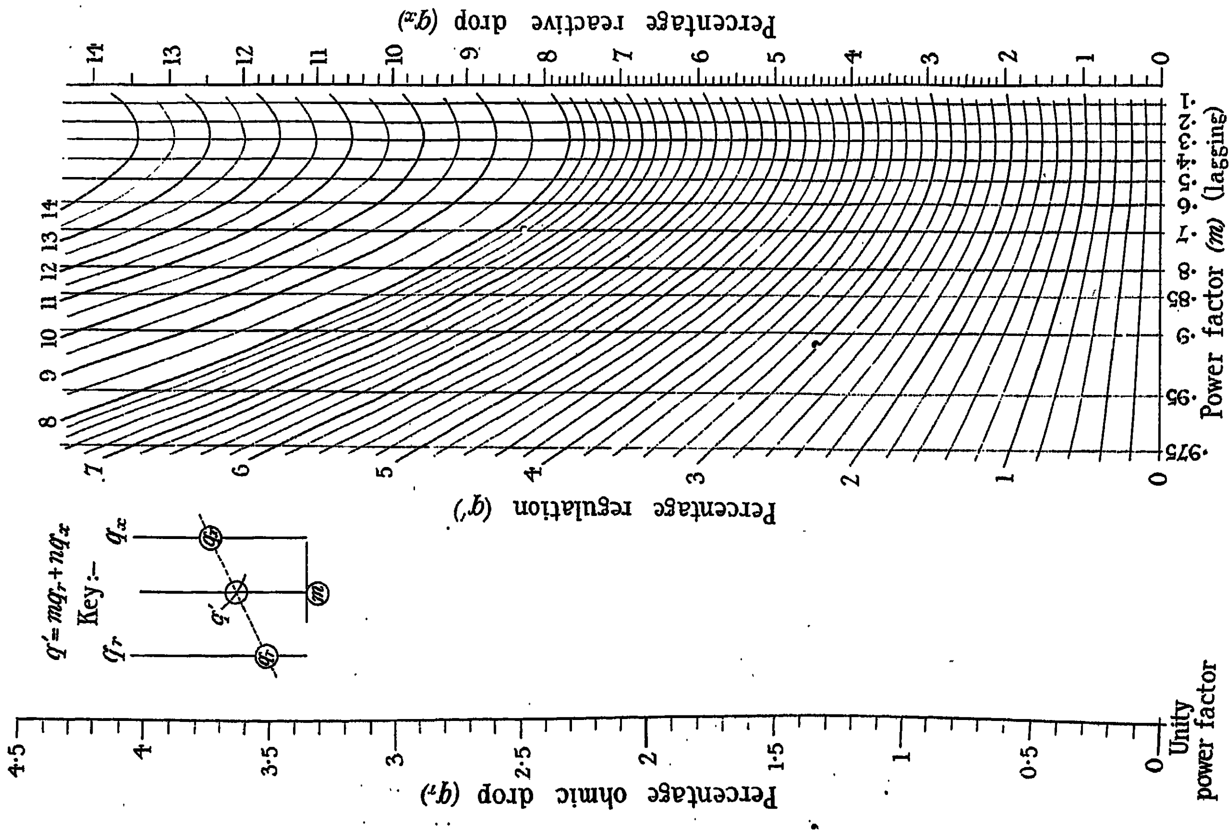

FIG. 3.—Alignment chart for determination of regulation of transformers.

Using these last values in Fig. 4 we find

$$q_r = 0{\cdot}83\ \%\,; \quad q_x = 6{\cdot}8\ \%$$

where q_r is the percentage copper loss, and q_x the reactance.

It will be seen that, in general, for comparatively low reactance the correction can be neglected without affecting the result beyond the limits of error commonly tolerated in calculations of this kind.

Example 3.—Regulation figures are required for a transmission line for which the ohmic drop and the reactance have been found to be 4·5 and 8 per cent respectively. The power factors are 1·0; 0·95; 0·9; 0·85; 0·8 and 0·7.

With $q_r = 4{\cdot}5$ per cent and $q_x = 8$ per cent we read from Fig. 3:

Power factor					
1·0	0·95	0·9	0·85	0·8	0·7
Regulation (approx.)					
4·5 %	6·75 %	7·5 %	8·0 %	8·4 %	8·8 %

From Fig. 4 we obtain the following corrections (rounded off):—

0·3 % 0·2 % 0·1 % 0·1 % 0·05 % 0·05 %

Adding these to the values above, the following figures result:—

Regulation (corrected)					
4·8 %	6·95 %	7·6 %	8·1 %	8·5 %	8·8 %

To make Fig. 3, which is primarily designed to cope with the case of the transformer, generally suitable for the case of the transmission line the range of both the q_r and q_x scales would have to be extended.

Depending on the user's ability to interpolate, the accuracy of the corrected readings is from 1/10 to 1/20 per cent. This compares well with commercial tolerances, which are not infrequently claimed to be as high as ± 20 per cent of the values put forward.

2. The Chord Diagram of Regulation.

In conclusion, mention should be made of a circle diagram that picturizes in a most simple and practical manner the relation as condensed in the American Institute formula, in any specific case of q_r and q_x. It has long been known, though rarely mentioned in textbooks, that in making q_r and q_x the sides of a right-angled triangle through the corners of which a circumscribed circle is drawn, the regulation as defined by Equation (2) is represented by the chord that is drawn through the vertex at an angle ϕ to q_r, where the power factor = cos ϕ. This is shown in Fig. 2, which serves to verify the relation:—

$$q' = AQ = AF + FQ$$
$$AF = q_x \sin\phi$$
$$FQ = ED = CD\cos\phi = AB\cos\phi = q_r\cos\phi$$

Thus $$q' = q_r\cos\phi + q_x\sin\phi$$

or $$q' = mq_r + nq_x \quad \text{(Equation (2)}$$

While this relation is well established, it is scarcely known that the correction term also, as in Equation (3), can in its essentials be represented in the simple diagram

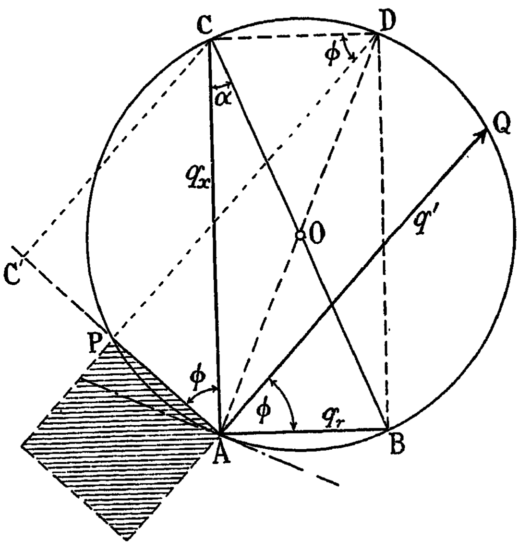

Fig. 5.

described; to this latter we propose to refer here as the "chord diagram of regulation," all quantities being represented by chords. It is only necessary to draw

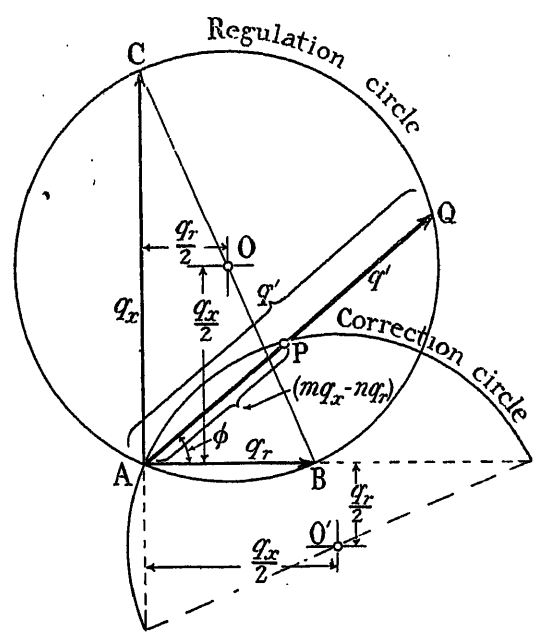

Fig. 6.

(Fig. 5) the chord that passes through the vertex A and is perpendicular to the regulation AQ to obtain from its length, when referred to the same scale to

which q_r and q_x are drawn, the basis of the correction term, that is

$$AP = mq_x - nq_r \quad . \quad . \quad . \quad (4)$$

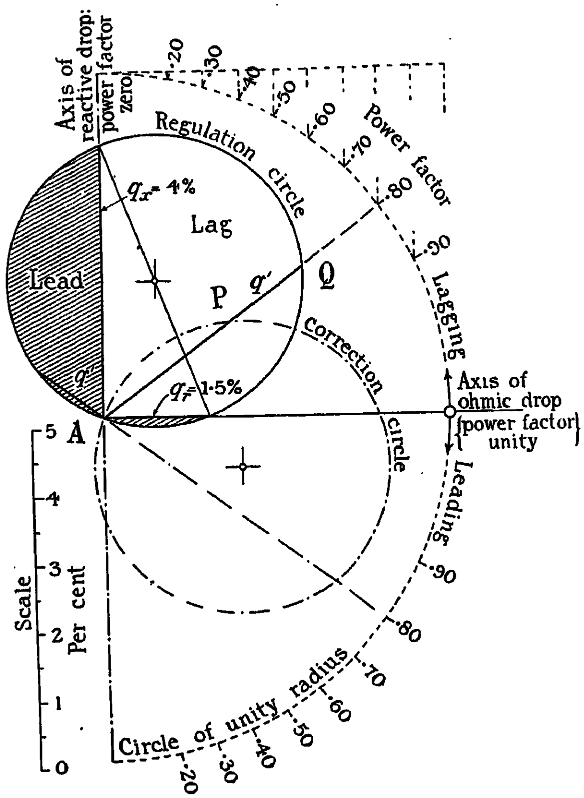

FIG. 7.

With this read off from the diagram, the correction term proper is obtained by raising to the second power the value read off and dividing the result by 200, as follows from the comparison of Equations (3) and (4).

Equation (4) is derived from Fig. 5 as follows:

$$\begin{aligned} AP &= AC' - C'P \\ AC' &= q_x \cos\phi \\ C'P &= CD \sin\phi = q_r \sin\phi \\ AP &= q_x \cos\phi - q_r \sin\phi \end{aligned}$$

or $$AP = mq_x - nq_r$$

When a second circle of the same radius is drawn, but with its centre displaced by 90° relative to the vertex A, the correction basis appears as the chord AP on the regulation chord itself, as shown in Fig. 6.

In Fig. 7 the complete chord diagram is drawn for $q_r = 1 \cdot 5$ per cent and $q_x = 4 \cdot 0$ per cent. On the unity circle the power factors (lagging and leading) are marked. A clear picture is obtained of the variation of the regulation q' and the correction factor as a function of the power factor. The hatched part of the circle corresponds to a leading power factor, and of this the segment to the left of the chord q_x refers to a voltage-rise.

In the particular case considered, we obtain the following figures for the regulation at a power factor of 0·80, lagging and leading respectively:

Power factor	0·80 lagging	0·80 leading
From Fig. 7, q'	3·60 %	1·2 %
Correction basis (AP) ..	2·25	4·15
Correction term $(AP)^2/200$	0·025 %	0·086 %
Regulation, corrected (and rounded off)	3·7 %	1·3 %

THE LEAFIELD COUPLED ARC.

By Major A. G. LEE, M.C., B.Sc., and A. J. GILL, B.Sc. (Eng.), Members.

(*Paper first received* 13*th January, and in final form* 25*th February*, 1925; *read before the* WIRELESS SECTION 1*st April*, 1925.)

SUMMARY.

The reasons for the introduction of coupled-circuit working are set forth, with some account of the preliminary experiments at Stonehaven and Northolt. The action of the coupled circuit in reducing harmonics and "mush" is explained.

Details of the design of the various portions of the circuit are given, together with an explanation of the tuning properties of the circuit.

The coupled circuit is found to give very constant frequency, and the factors contributing to this are dealt with in detail.

The reduction of harmonics and mush by the coupled circuit is very large, but the steps taken to reduce the residuum to still smaller proportions are described.

Section 1.

INTRODUCTION.

It is a matter of common knowledge that the Poulsen arc, if directly connected to an antenna, produces a great deal of disturbance to other wireless users on wave-lengths far removed from that of the arc. This disturbance is of two kinds, (1) the emission of harmonics, i.e. emissions which are definitely tunable and which can be heterodyned to a musical note, and (2) the emission of what has been called "mush." The latter manifests itself as a hissing sound and is usually found most strongly in the neighbourhood of the harmonic positions.

The cause of harmonics is to be found in the slight departure from sinusoidal form of the current in the oscillating circuit. Suitable design of the arc and the aerial circuit may reduce the strength of the harmonics below what is normally obtained from a valve oscillator of similar power on plain aerial, but in practice the harmonics, and more especially the mush, are still strong enough to give trouble.

The cause of mush is a little more obscure but is probably associated with the irregular frequency of the fundamental wave. The arc is an ionic contrivance and on a plain aerial connection has a frequency which, in the nature of the ionic action inside the arc chamber, cannot be expected to be very constant. Carson * has shown that if a sine wave has its frequency changed at a sinusoidal rate, or in other words undergoes frequency modulation, an infinite series of harmonics of the sum and difference of the fundamental and modulating frequencies is obtained.

When any one harmonic of this series happens to fit in with an harmonic resonant point of the antenna system, it gives rise to radiation on that frequency. With the arc, the fundamental frequency is undergoing frequent discontinuous changes and it is to be expected that the "harmonics" due to these irregular changes will form a continuous spectrum of disturbance, which is ready to emerge at any harmonic resonant point of the antenna.

In 1921, before the advent of broadcasting, the chief sufferer from the mush of the arc at Leafield was the Post Office station at Devizes. It was therefore decided to commence experiments on the introduction of a coupled circuit, with a view to the reduction of trouble.

From the theory outlined above it was to be expected that the provision of a primary oscillating circuit for the arc, in which both the capacity and inductance were concentrated, would tend to prevent the harmonic E.M.F.'s giving rise to currents of sufficient order to cause disturbance. The antenna system, with its distributed capacity and inductance, of necessity has harmonic resonance positions, so that the introduction of the primary circuit should cut down the harmonics before they get into the antenna system.

It was known that coupled circuits had been used in the early days of the Poulsen arc, but that their use had been discontinued, apparently on account of trouble with variable frequency. It was therefore decided to commence the experiments on a small scale on the 25-kW arc at Stonehaven. These experiments were completed in March 1922 and indicated that successful working of the coupled-circuit arc was possible and that the reduction of mush and harmonics was very considerable. Attention was next paid to the 30-kW arc at Northolt which was installed in July 1922, and the coupled circuit here proved equally successful.

It was then decided to embark on the provision of a coupled circuit for the arc at Leafield, which was completed and brought into commercial use in March 1924. The provision of this circuit involved radical changes in the layout of the plant and, as the station was in almost continuous commercial use, the operation of installation was necessarily a lengthy one.

Section 2.

DETAILS OF DESIGN OF THE LEAFIELD COUPLED CIRCUIT.

A diagram of the circuit as designed is given in Fig. 1. The values of inductance and capacity are those used on a transmitting wave of 12 350 m. The circuit can, however, be operated at wave-lengths from 8 500 m to 15 000 m.

In settling the electrical dimensions of the various parts of the circuit it was recognized that practical

* J. R. CARSON: "Frequency Modulation," *Proceedings of the Institute o Radio Engineers*, 1922, vol. 10, p. 57.

limitations would prevent the circuit being designed to give the maximum theoretical efficiency. The arc generators installed were known to operate satisfactorily with a value of $\sqrt{(L/C)}$ of about 150 to 270. This factor was given considerable weight in the choice of circuit constants.

It is known from theoretical principles that the efficiency of a coupled circuit is greater as the ratio

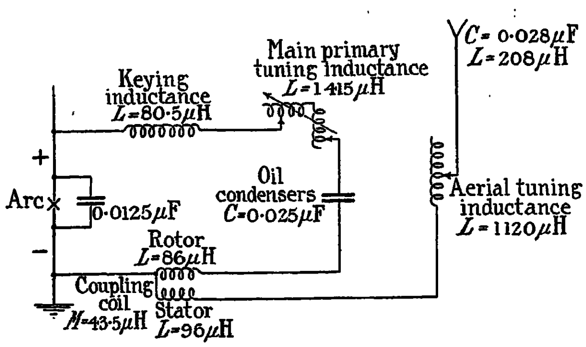

FIG. 1.—Diagram of circuit.

of C_2/C_1 increases. The value of C_2 is determined by the aerial, but the value of C_1 is to some extent a matter of choice.

There are limits, however, to the permissible reduction in capacity of the primary circuit, since the smaller condenser must operate at a higher voltage and this involves greater losses from leakage and corona, while the inductance value must be large, necessitating a large coil with greater losses.

The Poulsen arc functions most satisfactorily as a high-frequency generator when the ratio of direct current input to alternating output is $\sqrt{2} : 1$. When this ratio has values other than this there are large harmonic components present in the generated frequency. It has been found that in order to approximate to this ratio the value of $\sqrt{(L/C)}$ should not be less than about 100. For example, at a frequency of 25 000 cycles per second $LC = 40{\cdot}529 \times 10^{-12}$ and if $\sqrt{(L/C)} = 100$ then $L = 636\ \mu H$ and $C = 63\ 660\ \mu\mu F$.

Primary condenser.—In determining the most suitable value of condenser a table was prepared giving values of condenser voltage E, and values of $\sqrt{(L/C)}$ for a primary current of 250 amperes for various values of primary capacity and frequency, and is reproduced here as Table 1.

An examination of these figures led to the conclusion that the most suitable value of the primary condenser was 25 000 $\mu\mu F$ and that it should be suitable for a working pressure of 80 000 volts (R.M.S.).

There are three kinds of dielectric suitable for high-frequency condensers, namely air, mineral oil and mica. Investigation showed that air was out of the question, as its low dielectric strength and low permittivity would have made such a condenser impossibly large. The issue then lay between the oil and mica. The mica condenser is more compact and can be housed in smaller space; on the other hand the mica condenser is more expensive than an oil condenser of equivalent rating and cannot be overloaded with impunity, an event which might occur if the aerial became disconnected. It was therefore decided to adopt oil as the dielectric and to arrange the condenser in four units of 6 250 $\mu\mu F$ capacity.

Experiments were carried out to determine the suitability of commercial transformer oil as a dielectric medium at high frequencies. It is well known that the dielectric strength of such oil is improved when the oil is cleaned and dehydrated. The preliminary step was to determine whether the power factor was likewise improved by such treatment. Various methods of treatment were compared.

The oil selected was a light-grade non-sludging oil having the characteristics laid down in British Standard Specification No. 148 for insulating oils for use in transformers and oil switches.

The oil was not of the non-freezing variety and during installation it was exposed to heavy frost, which produced a semi-solid constituent. Tests were then made to determine whether the presence of this constituent had any influence on the power factor of the oil. It was recognized that the most convenient method of treating the oil would be by means of a centrifuge, and a De Laval dehydrator was obtained and tests carried out to determine whether such treatment was as effective in lowering the power factor as other methods of drying. Tests were also carried out to determine

TABLE 1.

Cycles per sec., f	LC	$C = 20\ 000\ \mu\mu F$		$C = 25\ 000\ \mu\mu F$		$C = 30\ 000\ \mu\mu F$		$C = 40\ 000\ \mu\mu F$	
		$\sqrt{\frac{L}{C}}$	E	$\sqrt{\frac{L}{C}}$	E	$\sqrt{\frac{L}{C}}$	E	$\sqrt{\frac{L}{C}}$	E
37 500	18×10^{-12}	212	53 000	170	42 500	142	35 000	106	26 500
30 000	$28{\cdot}1 \times 10^{-12}$	265	66 000	212	53 000	177	44 000	132	33 000
25 000	$40{\cdot}53 \times 10^{-12}$	319	80 000	255	64 000	212	53 000	159	40 000
20 000	$63{\cdot}3 \times 10^{-12}$	393	100 000	315	80 000	262	66 000	186	50 000

the effect of washing by contact with live steam on the oil prior to dehydration.

Most of the measurements of power factor and dielectric strength on samples of oil were carried out by the National Physical Laboratory and the summarized results of tests are as follows. The power factor measurements were made at a frequency of 25 000 cycles and the dielectric strength measurements were carried out at a frequency of 50 cycles per sec.

(1) Centrifugal dehydration is a satisfactory method of improving the power factor of oil, and by this means a normal power factor of 0·0003 in commercial oil can be lowered to 0·00005.

(2) The presence of a freezing constituent had no appreciable effect on power factor.

(3) Oil subjected to live steam and afterwards dehydrated was found to be unimproved. This appeared to be due to the presence of water particles in an extremely finely divided state. If such oil is subsequently heated for some time at 130° C. the high dielectric strength and low power factor appear.

(4) Heating the oil after plain dehydration gave an improvement in dielectric strength of 10 000 volts, i.e. from 52 000 volts to 62 000 volts in the standard gap of ½ in. dia. balls spaced 0·15 in. apart.

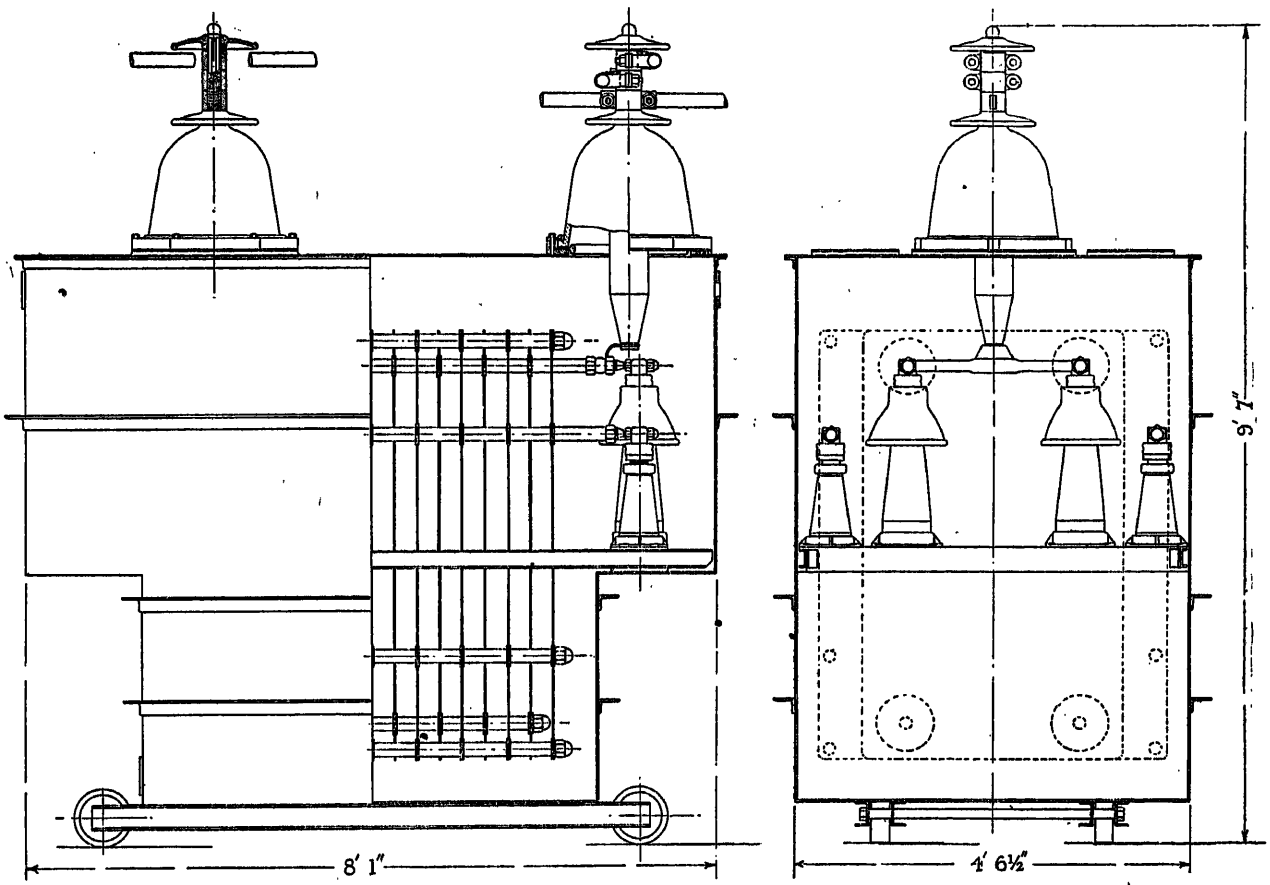

Fig. 2.—Arrangement of oil condenser. Capacity 6 250 $\mu\mu$F with oil of permittivity 2·2; working pressure 80 000 volts (R.M.S.).

The remaining point for investigation was the safe working stress for oil at high frequencies. There is an absence of published information on this subject. Peek * quotes comparative figures of the dielectric strength of a sample of oil between flat discs 2·5 cm diameter and 0·25 cm apart as 17 000 volts (max.) per mm at 60 cycles per sec. and 6 700 volts (max.) per mm at 90 000 cycles per sec. Here the oil subjected to the high-frequency voltage has only 37 per cent of its dielectric strength at low frequencies. Rough experiments were carried out to check these results and it was found that untreated transformer oil having a strength of 35 000 volts (R.M.S.) at 50 cycles on the standard gap when tested between flat plates ¾ in. apart at 55 000 cycles per sec. broke down at 35 000 volts (R.M.S.). Using dehydrated oil between plates having edges rounded to $\frac{3}{32}$ in. radius spaced 1 in. apart, a

* F. W. Peek, Jun.: "Dielectric Phenomena in High-Voltage Engineering," p. 165.

working pressure of 40 000 volts (R.M.S.) at 25 000 cycles per sec. could be safely used.

The strength of oil does not increase proportionately to the spacing between electrodes, and from these results it was estimated that in order to provide for a fair margin of safety at a working pressure of 80 000 volts (R.M.S.) at 25 000 cycles per sec. a spacing of 3 in. between electrodes should be maintained. Further experience indicates that this is on the liberal side and if it were possible to seal the tanks hermetically this spacing could be reduced.

During these experiments a small experimental oil condenser was built of 5 000 $\mu\mu$F total capacity in two units of 2 500 $\mu\mu$F each. The plates were spaced $1\frac{1}{2}$ in. apart and were of zinc $\frac{1}{16}$ in. thick. This condenser was in regular use at Northolt radio station as a coupled-circuit condenser operating at between 35 000 and 40 000 volts at 55 000 cycles. The only difficulty experienced was in obtaining suitable stock insulators to support the plates, and eventually the trouble was cured by making these of ebonite. The oil used in this case was not dehydrated.

In the condensers at Leafield (Fig. 2) the supporting insulators for both high-tension and low-tension plates are hollow porcelain columns arranged vertically. The merit of the vertical arrangement is that the insulators are in simple compression, and the dust particles cannot line up along the top surface of the insulator as they do in the case of horizontal insulators. Provision is made for the circulation of oil up through the centre of the columns. Vertical plates were adopted in preference to horizontal plates to avoid the risk of bubbles being trapped on the under surfaces. The horizontal rods carrying the plates rest on spherical shaped seatings on top of the insulators so that no bending moment can be communicated to the insulator; moreover, one end only of each rod is rigidly fixed, the other end having a small permissible travel to allow for differences of expansion. The spacing between all parts of h.t. and l.t. conductors is nowhere less than 3 in.

The design of lead-out insulator presented an interesting problem. The ordinary type of transformer or oil-switch bushing is unsuitable owing to the heavy capacity current passed by such bushings at high frequencies. In the experimental condenser referred to above, chemical bell jars of glass had been used, standing over holes in the tank cover through which the conductor passed. These had proved satisfactory and had been suggested by similar shaped insulators used on Admiralty condensers of lower voltage.

A similar type of bushing was adopted for the large condensers, using porcelain bell jars. This type of bushing (Fig. 3) has the advantage that its main insulation is air, while the porcelain provides mechanical support and excludes dust but carries a relatively small dielectric current. The distribution of potential between a line conductor and a plate having a circular hole through which the conductor passes has been investigated by Clerk Maxwell and others * both mathematically and by means of electrolytic cells having electrodes of analogous shapes.

* C. W. Rice: "Electrostatic Problems," *Transactions of the American Institute of Electrical Engineers*, 1917, vol. 36, p. 905.

It has been established in the limiting case, where the plate is plane and the conductor a line and where the dielectric is of uniform permittivity, that the equipotential surfaces are confocal hyperboloids of one surface, the focal point being the edge of the hole and the axis of revolution the conductor. The distribution of potential between such a plate and line is shown in Fig. 4 by equipotential surfaces and in Fig. 5 as a

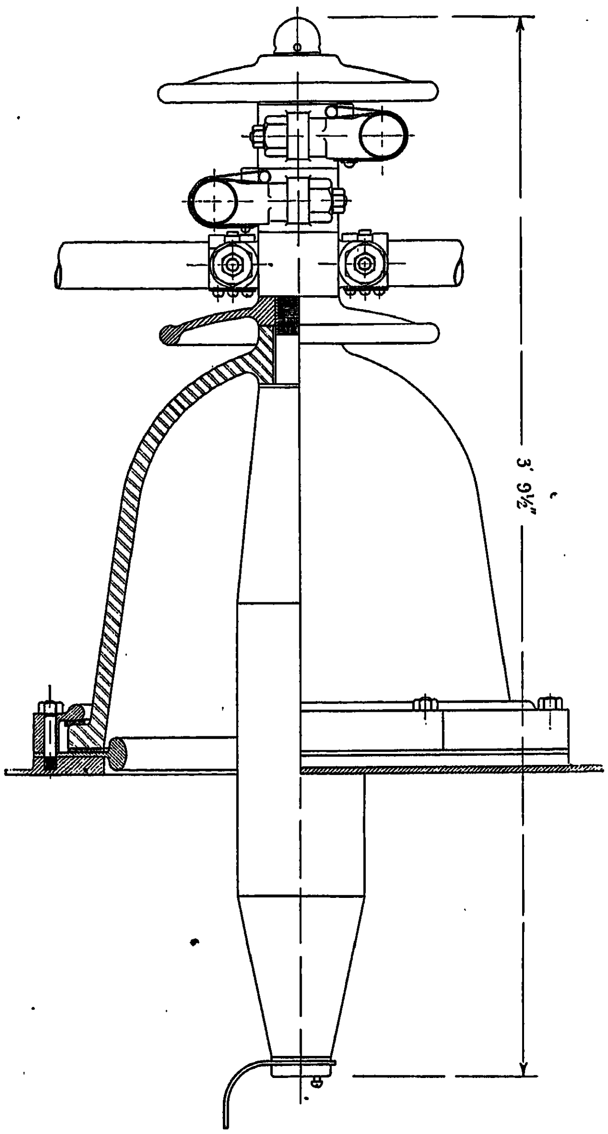

Fig. 3.—Bushing of oil condenser.

graph. The slope of this latter curve indicates voltage gradient. The gradient becomes infinity at the plane and at the line. In practice if we make the inner and outer conductors take the shape of confocal hyperboloids the distribution of potential between them will be unchanged and can be readily determined. From the shape of the potential curve it is clear that the potential gradient changes very rapidly near the edge of the hole and little or no advantage arises in making the

radius of the outer hyperboloid less than about 95 per cent of the focal radius C. If a tangent to the potential curve be drawn at this point it is seen that another different diameters of inner conductors. If the radius of the inner conductor is less than about $0 \cdot 33\ C$ the maximum gradient occurs at the surface of this con-

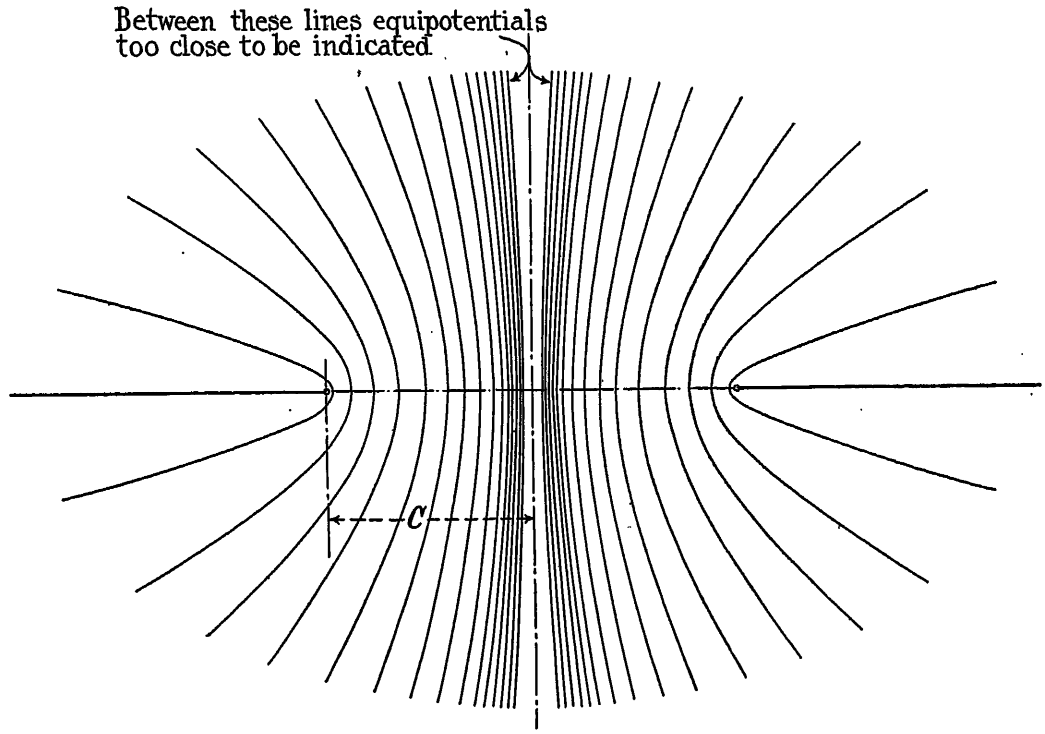

FIG. 4.—Equipotential surfaces between line and hole in plane. Radius of hole = C.

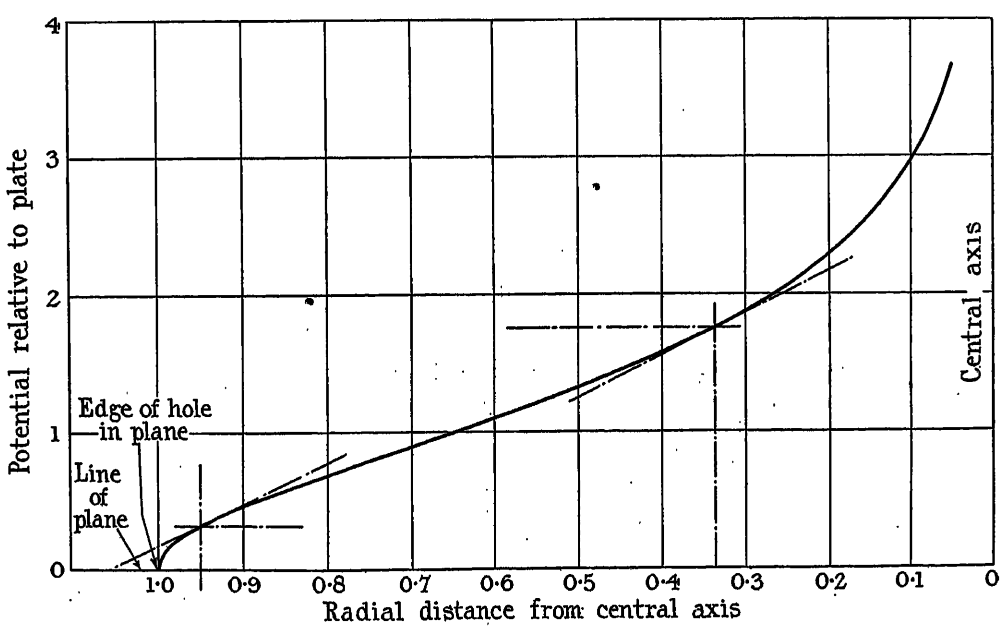

FIG. 5.—Distribution of potential between line and hole in plane.

similar tangent to the curve can be drawn at a radius of about $0 \cdot 33\ C$. This is more clearly shown in Fig. 6, where the radius of the outer conductor has been assumed to be $0 \cdot 95\ C$ and the maximum gradient plotted for ductor. On the other hand if the radius of the inner conductor is greater than $0 \cdot 33\ C$ then the maximum gradient occurs at the surface of the outer conductor.

The focal radius in the present case was taken as

20 cm and the inner conductor 7 cm radius. Taking the ultimate dielectric strength of air as 21 000 volts (R.M.S.) the voltage at which corona will appear will be $21\,000 \times 20/2{\cdot}4 = 176\,000$ volts (R.M.S.). The bushing should of course be worked well below this value to allow for the distortion of flux due to the outer conductor not conforming to a true hyperboloid.

The condenser has worked satisfactorily without sign of breakdown. The losses are extremely small and cannot be determined by temperature measurements as the surrounding air increases in temperature more rapidly than the condenser when the station is working.

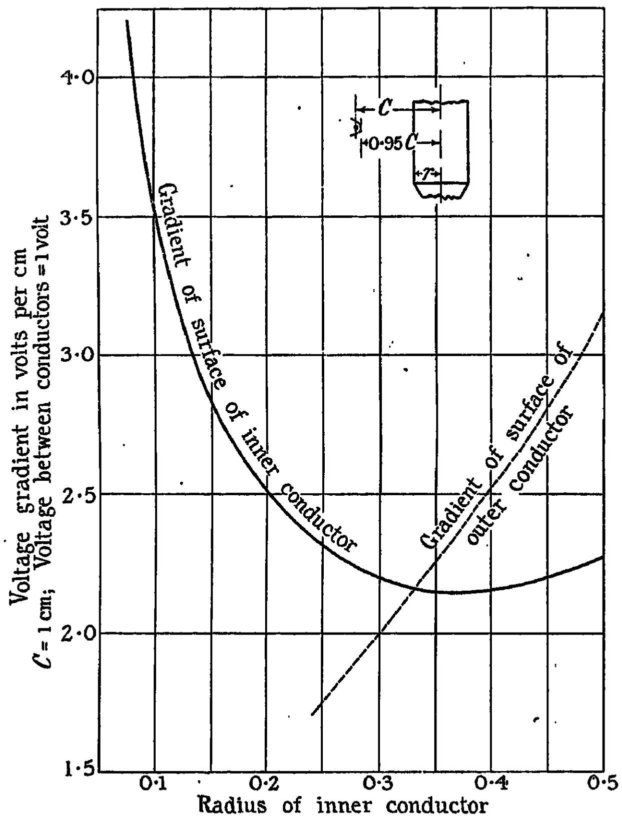

FIG. 6.—Maximum potential gradient with various sizes of central conductor.

Primary inductance.—At the time when this circuit was designed it was desired to obtain practical data of the performance of strip copper inductances in comparison with tubular and divided-wire types. As the strip pattern has great advantages from the points of view of cheapness and ease of manufacture it was decided to adopt this pattern at Leafield, as a divided-wire inductance was already installed there and direct comparison could be made.

Some type of variometer was required in the primary circuit, and in order to minimize the circuit resistance it was decided to combine this with the primary inductance. The inductance consisted of eight spiral coils, each coil consisting of seven turns of copper strip 4 in. wide × $\frac{1}{8}$ in. thick, the turns having a pitch of $3\frac{1}{2}$ in. and a mean diameter of 76 in. The coils were mounted with their axes vertical, the four lower coils being fitted on a moving carriage which ran on rollers and passed under the four upper coils, which were fixed in position. The vertical pitch of the coils was 10 in., this giving 6 in. clearance between the layers.

In subsequent experiments three coils were removed and the inductance now consists of three moving and two fixed coils. The whole is carried on a wooden

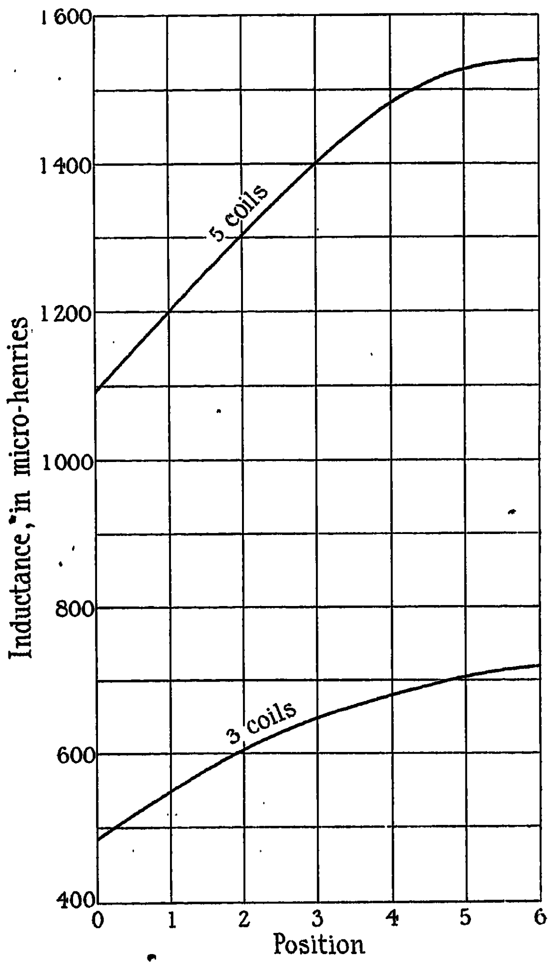

FIG. 7.—Position of variometer.

table 6 ft. above the floor, as it had been found that proximity to a concrete floor may appreciably increase the losses in a coil. The moving carriage is operated from the control platform by means of a handwheel and gears. It is thus possible to vary the wave-length of the primary circuit while the arc is running.

The variation of inductance by this means is quite satisfactory and is indicated in the case of three and five working coils in Fig. 7. The conductors are mounted directly on the wooden framework without the use of other insulation, as it had been found that thoroughly dry wood had better insulating properties at high frequency than most other materials. The wood used was mostly ash, but it was found that with this material prolonged drying by high-frequency currents was essential before its full dielectric properties

were developed. While under construction it was found that American whitewood had greatly superior qualities and this was substituted where possible. For some days before bringing the circuit into use and while the station was being operated on plain aerial the new primary circuit consisting of inductance and condensers was brought near resonance with the spacing wave so that a circulating current, which was gradually increased up to 150 amperes, was induced therein. At first the woodwork increased in temperature by about 60 deg. F., but after a few days this fell to normal. At one or two points charring occurred due to imperfect contact between the copper and wood causing corona. In one place only the ash supporting arm charred internally and had to be replaced by American whitewood.

Comparative measurements of resistance were made between this coil and the previously installed divided-wire inductance. This inductance is a single-layer solenoid of 22 coils of cable consisting of 1 600 insulated strands. These measurements show that the divided-wire type is decidedly superior ; this superiority becomes more pronounced at the shorter wave-lengths.

Coupling transformer.—It was decided to adopt separate inductive coupling as affording the readiest means of variable coupling between the primary and secondary circuits capable of adjustment while running. The coupling transformer consists of four coils, two of which are fixed and are in series in the aerial circuit. The remaining two coils are in series in the primary circuit and are rotatable inside the stationary coils.

The coils are built up of flat strip copper 4 in. × $\frac{1}{8}$ in. and pitched 1 in. apart between turns. The mean diameter of the fixed coils is 51 in. and each consists of four turns. The mean diameter of the rotatable coils is 37 in. and each consists of five turns. The copper is mounted on the wood framework, which in this case is of teak.

For reasons explained later, the losses in the coupling unit depend upon the tuning adjustment at which the circuit is worked and are found to be higher than desirable. It has therefore been decided to substitute the strip copper coupling unit by a divided-wire type.

The magnitude of M, the mutual inductance of the coupling coil, can be calculated for a resistance load in the secondary, if a current ratio I_2/I_1 is assumed. This, for the Leafield circuit, would be something slightly less than 10 μH. In practice, however, the secondary current has a reactive component which increases its impedance, and it is necessary to add something to the calculation made in this way in order to ensure that the power gets across. The coupling unit was therefore made variable up to about 90 μH, the best value (found by trial) being 43 μH. It was observed that the amount of coupling was not critical in its effect on the current obtained, and the value was finally decided by its effect on the constancy of frequency—too small a value making the arc less stable as it reduced to some extent the flywheel effect of the secondary circuit, and too large a value having the effect of making the aerial-swing relatively more important while the aerial current was not increased beyond the value which could be obtained on relatively smaller couplings. Under these circumstances the coefficient of coupling is approximately 3 per cent.

Costs.—Costs of some of the chief items of plant are given in Table 2.

TABLE 2.

Approximate Cost, including Erection and Overhead Charges.

	£
Condenser bank, including pipework, dehydrator, tanks and pumps	2 800
Primary inductance, including wooden framework, copper, operating gear and tools ..	480
Coupler, including woodwork, copper, insulators and metal fittings	160
High-tension busbars and supports	150
Miscellaneous items, meters, switches, screens, etc.	250

Section 3.

TUNING OPERATIONS ON THE COUPLED CIRCUIT.

Apart from the fact that the Poulsen arc has a somewhat unique cycle of operations, the ordinary theory of the oscillation of coupled circuits may be applied to elucidate the operation of tuning. Many papers have been written on the discontinuous frequency-changes which occur in the operation of valve transmitters with coupled circuits, of which one of the earliest was by Townsend.* Townsend described a graphical method of explaining the discontinuous frequency-changes. His description of the actions which take place may be applied to coupled-circuit arc working, but as his diagrams are in terms of the square of the wave-lengths it is thought that the following method of explaining the action is perhaps somewhat simpler. The diagrams and theory are of course elementary but are a necessary preliminary to the particular action of the arc on coupled circuits.

Fig. 8 shows the changes of the several reactances in the primary circuit as the frequency generated is altered. The primary circuit reactance $\omega L_1 - (1/\omega C_1)$ over the portion of the frequency range considered is almost a straight line. It can be shown that the effect of the current in the secondary circuit is to impress an E.M.F. in the primary, the reactive component of which, $(-\omega^2 M^2/Z_2^2)X_2$, may be regarded as an additional inductance or capacity in the primary circuit depending upon the phase of X_2. The sum of these two reactances forms the net reactance of the primary circuit. It is well known in this case that the frequency generated will be such that the net impedance of the primary circuit is zero. In other words, for the particular diagram given (in which the primary and secondary circuits are both tuned to the same frequency f_0), the arc will oscillate at the points f_1 or f_2, where

$$\left(\omega L_1 - \frac{1}{\omega C_1}\right) - \frac{\omega^2 M^2}{Z_2^2} X_2 = 0$$

* J. S. TOWNSEND: "Oscillations obtained by coupling a secondary circuit with a continuous-wave valve oscillator," *Radio Review*, 1919–20, vol. 1, p. 369. Since the paper was written the authors' attention has been called to an earlier article on the subject by HUMBY and SCHONLAND: "Wave-lengths radiated from oscillating valve circuits," *Electrician*, 1919, vol. 83, p. 443.

These frequencies are given for the isochronous case by the ordinary theory of coupled circuits, viz.

$$\omega_1 = \frac{\omega_0}{\sqrt{(1+k)}}; \quad \omega_2 = \frac{\omega_0}{\sqrt{(1-k)}}$$

where $\omega_1/(2\pi)$, $\omega_0/(2\pi)$ and $\omega_2/(2\pi)$ are the frequencies f_1, f_0 and f_2 respectively, and k is the coefficient of coupling.

Tuning of the circuit may be effected by keeping the secondary circuit constant and altering the inductance of the primary. This is the method employed at Leafield. Further lines such as those shown dotted may be drawn on the diagram to represent this tuning by alteration of inductance, and the interception of these lines with the curve of reactance due to the secondary circuit gives new oscillation points such as f_3 and f_4.

the line still further to the right, it ceases to cut the negative secondary reactance curve, and the oscillations therefore suddenly jump to a much higher frequency represented by f_5, where both reactances have changed sign and we have again the equality $\omega L_1 - (1/\omega C_1) = (\omega^2 M^2/Z_2^2)X_2$. These effects are depicted in Fig. 9, in which the dotted lines represent the frequencies obtained graphically in this way.

On retracing our steps by moving the line $\omega L_1 - (1/\omega C_1)$ from right to left, it is now the high-frequency oscillation which has taken possession of the arc and we have frequencies given by the intersection of this line with the positive values of $(\omega^2 M^2/Z_2^2)X_2$. On passing beyond the positive maximum of reactance due to the secondary, the frequency generated again makes a sudden jump, this time to the low side.

In this discussion we have neglected the effect of resistance in order to make the matter more clear. It

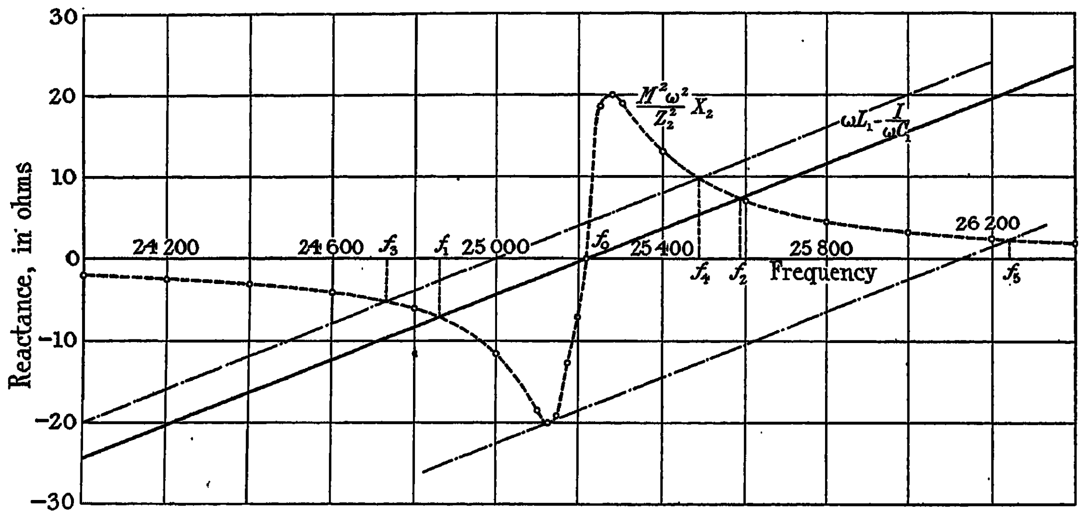

FIG. 8.—Variation of effective reactance of the primary circuit.

Now, in general, the arc will only oscillate on one frequency at a time if it has a choice of two frequencies which are not harmonically related. This is because the extinction period of the arc forms a discontinuity which can only fit one cycle of operations.

With a coupled circuit such a cycle of operation is normally stable unless certain limits are exceeded, because a change from one mode of oscillation, say f_1, to the other, f_2, entails an almost complete reversal of phase in the secondary circuit, a process which can only be carried out by the expenditure of a certain amount of energy.

We will now trace out the effects which occur as the primary inductance is altered from a low-frequency resonance value to a high frequency. As the line $\omega L_1 - (1/\omega C_1)$ is moved parallel to itself from left to right of the diagram, oscillations commence at a low frequency, gradually rising in frequency as the line is moved to the right. It will be seen that near the negative maximum of the curve representing reactance from the secondary circuit, the frequency-change for a given movement of the line becomes smaller. Moving

is obvious, however, that as we approach the isochronous frequency from either side the effective resistance introduced by the secondary into the primary circuit will increase. For instance in the Leafield case, if it were possible to reach the isochronous frequency the effective resistance introduced by the secondary into the primary would be over 40 ohms.

We shall therefore approach a point when the total effective resistance of the primary circuit is too great for the negative resistance developed by the arc to handle and the oscillations will stop, starting again immediately at the new frequency position determined by the tune of the primary circuit in relation to the reactance from the secondary, as already described. The area enclosed by this oscillation hysteresis effect will, therefore, be smaller than that shown by the dotted lines in Fig. 9. The heavy lines in Fig. 9 indicate the actual frequencies obtained as the tuning of the primary circuit of the arc at Leafield was altered. The arrows on both the dotted and heavy curves indicate the direction in which the tuning was effected. The points of interest in these latter curves are:

(1) The hysteresis area is much smaller than that calculated, in which no allowance was made for a limit to the negative resistance effect of the arc.
(2) The hysteresis is not symmetrical about the isochronous position, a fact which is reflected in the current ratios given later.
(3) The frequency-change is very flat as we approach the positions of frequency discontinuity.
(4) A further point of interest is the difference in the calculated and observed frequencies, part of which is due to minor inductances and capacities, e.g. leads which were not allowed for in the calculation, and a further part which is due to the well-known property of an arc giving a frequency lower than that due to the LC values of the circuit, on account of the extinction period forming part of the total cycle. It has been calculated that the extinction period of the arc at Leafield is of the order of 1 per cent of the total period.

The difference between the two frequencies f_1 and f_2 is in agreement with the coupled-circuit formulæ already given for the isochronous position, viz.

$$\omega_1 = \frac{\omega_0}{\sqrt{(1+k)}}\,;\quad \omega_2 = \frac{\omega_0}{\sqrt{(1-k)}}$$

except that the absolute value is affected by the extinction period as above stated.

The arc at Leafield is operated with both marking and spacing waves. It will be seen, therefore, that provided both these waves are kept sufficiently far away from the frequency discontinuity position, the arc can be operated in a quite stable manner.* In practice, operation on the low-frequency side is found to be more stable than on the high-frequency side, and in addition this side gives a larger secondary current. The actual operating tuning point is very slightly beyond the isochronous position, which in practice is far enough away from the discontinuity position to be perfectly stable. It will be realized that, if operation on the low-frequency side is decided upon, the secondary circuit has to be set at such a value as to enable the frequency required to be attained.

Fig. 10 shows the ratio of secondary to primary current as the tuning of the primary circuit is altered. It will be seen that tuning the primary circuit from the low-frequency side gives the larger current ratio. No explanation has been found for the early break on the high-frequency side, but it may possibly be associated with stray capacity couplings.

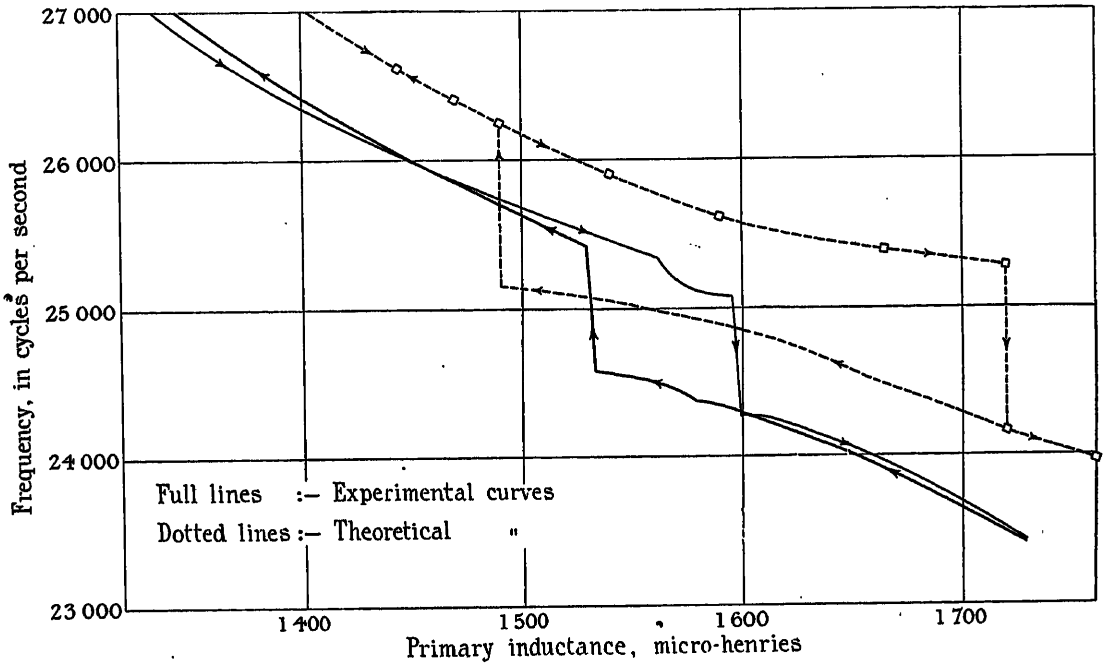

FIG. 9.—Variation of frequency generated as tuning of primary circuit is altered.

The point where the two curves cross is, as nearly as can be estimated, at the isochronous position. It will be seen that a larger current ratio is obtained beyond the isochronous position, a phenomenon which has been given the name of "Ziehen" by German writers.

The distinction between the isochronous tuning position and the isochronous frequency may perhaps be emphasized here. When the circuits are tuned to the same frequency, or are isochronous, the frequency generated on the "low side" is lower than the isochronous frequency by 370 cycles per sec. The current in the secondary circuit is therefore out of phase with the voltage, and the circuit presents reactance to the current.

* This has already been reported by PESSION: "Funzionamento dell' Arco Poulsen ou circuiti accoppiati," *L'Elettrotecnica*, 1923, vol. 10, p. 890, and it was also a feature of the experiments at Stonehaven and Northolt in 1922.

It is obvious that as we pass the isochronous position we shall get nearer the frequency at which the secondary circuit is resonant, and hence I_2/I_1 will increase. In actual working with the arc, however, the secondary current only increases a short way beyond the iso- in the primary circuit compared with that in the secondary, the less power is wasted in the primary coil and condenser and, what is more important, in the arc itself. It is this possibility of getting a ratio I_2/I_1 greater than unity which permits of the coupled arc

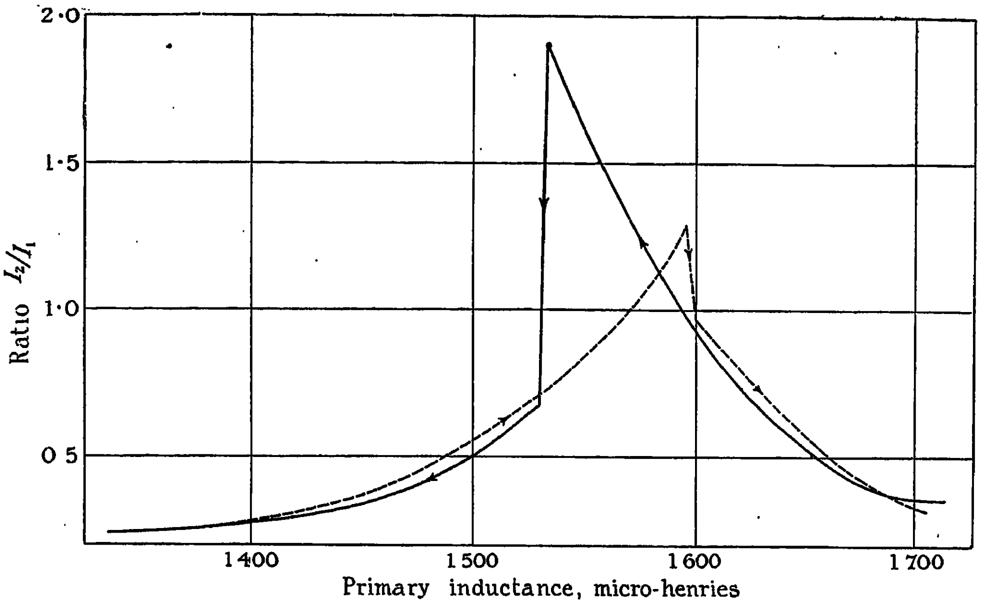

FIG. 10.—Ratio of secondary to primary current as tuning of primary is varied.

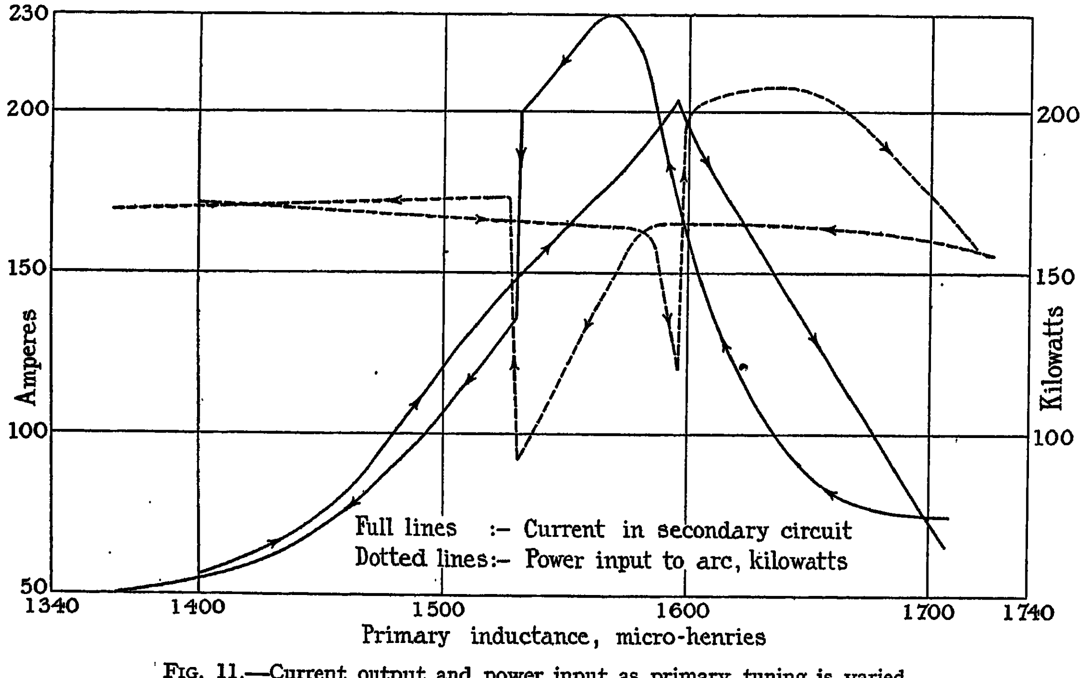

FIG. 11.—Current output and power input as primary tuning is varied.

chronous position, on account of the various limitations on output involved in the design of the particular arc, although the ratio of currents and also the efficiency continue to increase. With regard to the latter point, it is obvious that the smaller we can make the current being operated at an efficiency equal to or greater than that obtained in plain aerial working.

Fig. 11 shows a curve representing the actual currents obtained on various tuning adjustments of the arc at Leafield, from which the ratios in Fig. 10 were calculated.

This curve was obtained by keeping the d.c. voltage approximately constant. The power input is also plotted, from which it may be seen that the efficiency rises considerably as the isochronous position is passed.

Section 4.

Other Forms of Coupling.

The inductive type of coupling has been used in all the experiments at Stonehaven, Northolt and Leafield because it is relatively cheaper than condenser coupling and can be made continuously variable. The Northolt circuit has an auto-transformer coupling, while the Stonehaven and Leafield circuits are transformer-coupled.

The object of fitting a coupled circuit is, however, the reduction of harmonics and mush and, theoretically, it is fairly obvious that a capacity coupling offers advantages in this direction inasmuch as the harmonic voltage impressed on the secondary circuit is much reduced by employing a capacitative in lieu of an inductive coupling, the voltages in the two cases being $I_1/(pC_m)$ and pMI_1 respectively, $p/(2\pi)$ being the frequency of the harmonic and I_1 the harmonic current in the primary. It will be seen that the voltage decreases with the frequency in the case of the capacitative coupling, while it increases with the frequency with inductive coupling.

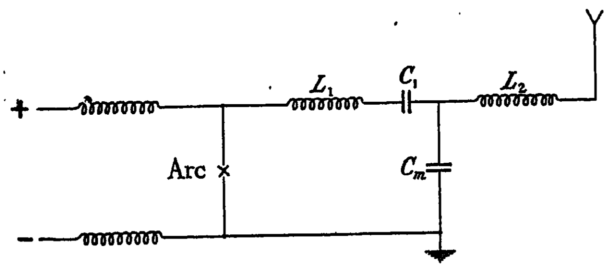

Fig. 12.—Capacity coupling.

Fig. 12 gives the circuit diagram in the capacity case. This circuit has been tried out on the arc at Northolt. On the first attempt the tuning was found to be critical and the arc unstable. A second attempt was, however, more successful but the following experimental facts emerged. With weak coupling and the circuits in approximately the isochronous position, the low-frequency oscillation f_1 was unstable, but the high-frequency f_2 was stable. With tighter coupling it was found that the low-frequency oscillation f_1 was stable but the f_2 frequency unstable. With couplings in between these two values both f_1 and f_2 were stable but the tuning could not be carried far beyond the isochronous position on account of the closeness of the frequency discontinuity. The value of the coefficient of coupling in these tests was of the same order as in the inductive tests. The results indicate that, while stability can be obtained, there is some inherent instability in the capacitative case in the arrangements at Northolt. The efficiency is also low because the tuning cannot be carried beyond the isochronous position.

Listening tests were made for harmonics around 400 m at Dollis Hill, about 6 miles from Northolt, where it was found that the higher harmonics were reduced but the lower harmonics were unaffected. The results are complicated by the possibility of direct radiation from the primary circuit, and at this distance it cannot be entirely excluded from our reckoning. These experiments have only recently been carried out and some more work requires to be done to remove, if possible, the causes of instability and low efficiency.

An interesting feature of the tests is the relatively very small current in the coupling condenser C_m during the f_1 oscillation, and the relatively large current, approximately equal to $2I$, during the f_2 oscillation. These are, of course, to be expected from the theory of coupled-circuit oscillations. The same phenomenon is, of course, present in the inductive types of couplings. In the transformer type of coupling, however, the field in the coupling coil during the f_1 oscillation is approximately double that due to I_1 or I_2, as the currents assist. In the f_2 oscillation, on the other hand, the currents are opposite in phase and the net field is small. The losses in the coupling coil are therefore larger in the f_1 than in the f_2 type of oscillation.

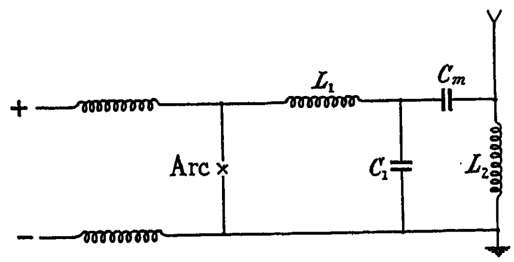

Fig. 13.—Capacity coupling.

Another type of condenser coupling which has been recommended is a small condenser connecting the high-voltage points of the two inductances L_1 and L_2 (see Fig. 13). Calculations which have been made for this circuit indicate a very small voltage across the coupling condenser during one type of oscillation, and an excessively large voltage during the other type. The latter possibility has discouraged any trial of this type of coupling.

Section 5.

Constancy of Frequency.

It is well known that an arc on plain aerial excitation is liable to unsteady frequency variations, and one of the pleasing features of the coupled-circuit working at Leafield is the remarkable steadiness of the frequency and the purity of the note.

The modern demand for high selectivity in the receiver requires very great steadiness in the transmitted frequency. As time goes on, the crowding together of wireless services will demand that more and more attention be paid to this point. Some inquiry has therefore been made in regard to this feature of coupled-arc working.

An instrument was designed for the purpose of

observing these small changes of frequency of the order of a few cycles per second. It consists of a heterodyne oscillator beating with the signal to give a beat note of approximately 1 000 cycles per sec. The output of a second low-frequency oscillator, tunable to 1 000 cycles per sec., is placed in series with the telephones and the beats between the two 1 000-cycle notes are reduced to zero. Any variation in the signal of even a fraction of 1 cycle per second is then immediately audible as a slow beat between the two notes. The tuning condenser on the 1 000-cycle oscillator is calibrated in terms of cycles per second, so that frequency variations can be read off directly. Precautions have to be taken that the instrument itself does not vary its frequency. Over short intervals of time this is easily attained, but over long intervals of time its absolute frequency is checked by highly accurate wave-meter measurements. In what follows, the instrument will be referred to as a "frequency meter" for shortness.

The following are some of the observations made on the Northolt arc, which normally is less steady than that at Leafield, and it was thought that this might be a function of the higher frequency at which the former arc is worked.

(1) *Arc with a resistance load of 2 ohms in the primary circuit and the aerial circuit disconnected.*—It was found that the variation of mean frequency was not great, but that the beat note on the frequency meter was ill-defined, indicating that the variation was too rapid to allow a musical beat note to be obtained. No quantitative idea of the magnitude of the variation was obtainable.

(2) *Similar conditions of circuit, but with a large condenser shunted across the arc.*—The frequency variations were the same as in case (1).

(3) *Arc with normal circuit coupled to aerial with auto-transformer coupling.*—The beat note was now found to be clear and musical. The mean variation on the frequency meter was of the order of 2 to 3 cycles per sec. Weather calm.

(4) *Conditions of* (3) *repeated but with a large condenser shunted across the arc.*—The beat note became even clearer and more musical than in (3) with the same order of mean variation.

These tests indicate that the arc itself is unstable, but that the coupled circuit exercises a stabilizing tendency and that the addition of a condenser in shunt across the arc improves the stabilizing properties of the circuit. The instability of frequency of the Northolt arc set was found not to be due to the high frequency but to aerial variations.

Similar results to these have been obtained at Leafield, except that in the case of coupled circuit without the shunt condenser across the arc the beat note on the frequency meter is definitely not good.

What may perhaps be called the steady "instantaneous frequency" obtained with coupled-circuit working is partly the explanation of the enormous reduction of mush which is observed. As explained at the commencement of the paper, mush is thought to be due to the very rapid, though possibly small, changes of fundamental frequency.

The property of a coupled circuit of reducing permanent or prolonged frequency-changes is, of course, obvious from a reference to Fig. 8. If, for instance, the arc is oscillating at a point such as f_1, and the frequency tends to increase, due, say, to some irregularity in the extinction period, such as a short period of excess ionization causing earlier ignition, then the secondary circuit will put back into the primary circuit a larger value of $(\omega^2 M^2/Z_2^2)X_2$. In this particular mode of oscillation, f_1, this quantity acts as an effective inductance in the primary circuit, and its increase tends to slow down the oscillation and to some extent to compensate for the change of frequency. The order of compensation for small changes of this kind has been calculated for various portions of the curve, and in general it may be stated that the magnitude of the variations is halved. This reduction is not large and would not be sufficient to explain the remarkable difference in purity and steadiness of note between plain aerial and coupled-circuit working.

A change of frequency of the current in the secondary circuit, however small, cannot take place instantaneously. This, in itself, would be sufficient to explain the purity of note, due to the suppression of rapid variations, when the signals are heard at a considerable distance. The same phenomenon of purity of note is, however, evident at the station itself, where of course the current in the primary circuit is heard strongly. The stabilizing effect of the condenser shunted across the arc also appears to be of some importance.

There seems to be a possibility that the secondary current has some action upon the irregularities liable to occur in the arc cycle, more particularly those in the extinction period. Unfortunately the efforts made to get experimental evidence of this by oscillograph records have failed, due to the enormous stray magnetic and electric fields at the wireless station clouding the phenomena which it was desired to observe.

Such oscillograph observations as were made, however, indicated that with the shunt condenser across the arc the extinction voltage was slightly higher than the d.c. voltage across the arc. It is fairly obvious that the particular shunt condenser employed ($0 \cdot 0125\ \mu F$) is large enough to absorb the surplus current when the arc is finally blown out, thus preventing the rise of voltage which normally occurs at extinction. In the normal arc circuit the arc becomes unstable when the current is reduced to a certain small quantity, and at this point the magnetic field blows out the arc suddenly, causing a rush of current into the external circuit. This in turn produces a rise of voltage, due to the inductance of the circuit. The rise in voltage tends to maintain the arc and delay the blow-out slightly, and the arc is stretched out farther before it finally goes out. With the shunt condenser, however, the surplus current is absorbed without producing much rise of voltage, and the arc should therefore go out at a shorter length than in the normal case.

If it may be assumed that the ionization in the gap between the electrodes is dependent to some extent upon the final distance of the arc from this gap, then

the longer arc will leave less ionization in the gap than the shorter arc given by the shunt condenser condition. Further, the low extinction voltage and short final arc of the shunt condenser condition are more favourable to action by a small external E.M.F., such as that acting from the secondary circuit. If this E.M.F. is increased from any cause, the suggestion is that the final arc length is increased and the ionization in the gap lowered. This in turn will delay the re-ignition and cause a lower frequency to be generated. Now if the primary circuit tends to get out of step with the secondary, due, say, to excess ionization causing early ignition, the secondary current will not change instantaneously and hence the phase of the two currents will change. The normal phase relations at the f_1 oscillation point are such that the secondary current is about 10 degrees behind the primary current. The magnitude of the E.M.F. in the primary, due to the secondary current, is therefore of the order of 330 volts at the moment of extinction. The rate of change of this E.M.F. at this point is approximately 33 volts per degree shift of phase. An increase of the phase difference between primary and secondary will therefore produce a larger reaction voltage which, it is suggested, tends to compensate by reducing the ionization in the gap.

The voltage at ignition will also be affected by the secondary reaction voltage, but as the actual ignition voltage is in the neighbourhood of 3 400 volts it is unlikely that the reaction voltage will have much direct effect on the ignition, except, as suggested, through the medium of the ionization.

Some confirmation of this suggestion is given by the following experiments.

(1) Using the coupled circuit in both cases, the frequency generated was found to be higher by 40 cycles per sec. when no shunt condenser was employed than with the shunt condenser. Making allowance for the normal compensating effect of the coupled circuit, this is equivalent to a change of 80 cycles per sec. in the primary frequency, which is further equivalent to a reduction of the extinction period to two-thirds of that in the shunt condenser case. Making the usual assumption that, during the extinction period, the condensers are charged at constant current, the charging rate for the shunt condenser case is two-thirds of the without-shunt-condenser condition. Therefore the reduction of the extinction period is given both by calculation and experiment.

The peak value of the ignition voltage was measured in both cases and was found to be nearly the same, viz. 3 200 volts in the without-shunt-condenser case, against 3 400 volts with shunt condenser.

It follows, therefore, that if with the 50 per cent longer time interval of extinction the ionization, as indicated by the ignition voltage, is nearly of the same order as in the without-shunt-condenser case, then the ionization must have started at approximately a 40 per cent higher level, which agrees moderately well with the known smaller extinction voltage in the shunt condenser condition.

(2) The stabilizing tendency of the shunt condenser should only apply to the low-frequency mode of oscillation, f_1. In the f_2 mode of oscillation the phase relationships of the currents in the two circuits are reversed and, moreover, the reaction E.M.F. is now acting in a reversed direction, the net result being a tendency to increase instability for rapid fluctuations.

Actual listening tests show the mush to be more pronounced when oscillating on the high-frequency than on the low-frequency side.

(3) A resistance of 5 ohms was inserted in the shunt condenser circuit. The effect of this would be to reduce seriously the current-absorbing properties of the shunt condenser. Actual listening tests at the station showed the mush to be much worse with this arrangement.

The above discussion refers to the instantaneous irregularities of frequency and we will now turn our attention to the larger and slower variations which are liable to occur.

Some of the most probable of the causes of such variations are as follows :—

(*a*) Changes of d.c. voltage across the arc.
(*b*) Changes in ionization, due to variation in quantity of methylated spirit fed to the arc.
(*c*) Change in the capacity of the primary condenser, due to alteration of temperature.
(*d*) Swing of aerial affecting capacity or inductance.
(*e*) Rain or mist affecting leakage or electrostatic capacity of aerial.

As already stated, the coupled circuit only halves the variation due to a permanent or semi-permanent cause, and it is therefore of importance to reduce these effects as much as possible by correct design or management.

These items were dealt with individually, with the following results.

(*a*) No variation in frequency due to changing the d.c. supply within the limits ordinarily used could be traced.

(*b*) Starving the arc of methylated spirit produces a change of 10 cycles in the frequency; and flooding the arc with the spirit produces a similar change. These are, however, extreme conditions rarely met with in practice.

(*c*) After a prolonged run the temperature of the air in the circuit room rises, and this causes a small, slow change in the frequency, through alteration of the capacity of the condenser; on the marking wave this is compensated by a carbon resistance in the keying circuit, which has an opposite effect on the frequency as the temperature rises.

(*d*) The top, flat portion of the aerial at Leafield consists of 16 parallel wires strung up tightly, 30 ft. apart, and these do not appear to contribute anything appreciable to the frequency variation. The down-lead consists of extensions of these 16 wires coming down in fan-shaped formation to two points near the leading-in insulator, the height of the latter above ground being about 20 ft.

The experiment was performed of exciting the aerial with a small valve oscillator and observing the variations of frequency on a windy day by means of the frequency meter and at the same time observing the movements

of the aerial. The maximum variation of frequency observed was 16 cycles per sec. (which on coupled circuit working would be reduced to 8 cycles) and this was definitely correlated with the movements of the wires in the bottom portion of the fan-shaped down-lead, where the wires were in close proximity. Calculation shows that changes in capacity and inductance of a multiple antenna are greatest when the wires are close together, and that if there were no external loading these changes would tend to compensate each other in their effect on frequency. The effect of the aerial tuning inductance is, however, to render of small effect any change in the inductance of the antenna, and the capacity changes predominate. Arrangements are therefore being made to modify the down-lead with a view to reducing this swinging effect of the separate wires. The variation of frequency in normal weather is only 2 to 4 cycles per sec. and in certain windy weather, particularly with S.W. winds, the variation is of the order of 6 to 8 cycles. It is hoped that this latter variation will be reduced by the alterations contemplated.

(*e*) It might be expected that the dielectric constant of the air under the antenna would be increased by the presence of moisture, but there appears to be no material alteration of the aerial constants from this cause. Leakage might also be expected to change the frequency generated in the case of coupled-circuit working, but there does not appear to be any appreciable effect due to this cause. No difficulty exists in starting up on a wet day and it is probable than any leakage dries out quickly.

Section 6.

Elimination of Harmonics.

The lower-frequency harmonics which had formerly troubled Devizes and other wireless stations were found to have been eliminated by the coupled circuit, but no improvement was observable on the broadcasting band of wave-lengths which were still interfered with by some of the higher harmonics of Leafield.

Attention was therefore paid to tracing the source of these harmonics at the station itself and suppressing them by various expedients.

The apparatus used for this purpose was of two kinds:

(1) A small frame coil tunable to the broadcasting range and with a small 2-volt lamp as indicator.
(2) A portable heterodyne oscillator covering the broadcasting range.

Of the two kinds, the latter proved more generally useful, as it could be carried about outside the station and would still pick up the harmonics at a comfortable strength.

It will be remembered that in Section 4 the relative merits of condenser and inductive coupling were discussed and it was shown that inductive coupling tended to pass the higher harmonics. At Leafield, however, the primary circuit condenser has a capacity to earth of 0·002 μF which, as will be seen from the diagram in Fig. 14, acts as a shunt across the coupling coil for these higher harmonics. Owing, however, to the somewhat congested layout of the circuit at Leafield, there is fairly close proximity between portions of the primary and secondary circuits, with a possibility of stray coupling between these points.

The keying coils, on account of their proximity to the aerial coil, probably transferred the harmonics directly to the aerial coil without passing through the shunted coupling. The steps taken to reduce this effect were to shunt the keying coils by placing a condenser of 0·01 μF across them and by connecting this condenser to earth through a condenser of 0·001 μF, the object of which was to keep the harmonic potential of the keying coils as low as possible. A small resistance was also placed in the key side of the coils for damping purposes.

The condenser shunted across the arc was next found to be a source of harmonics, as was proved by the great reduction of the series of harmonics when the condenser was removed. This condenser, however, performs too important a function in stabilizing the frequency and in increasing the current output to allow it to be removed. Various experiments in the nature of adding damping to this circuit were made and were found to

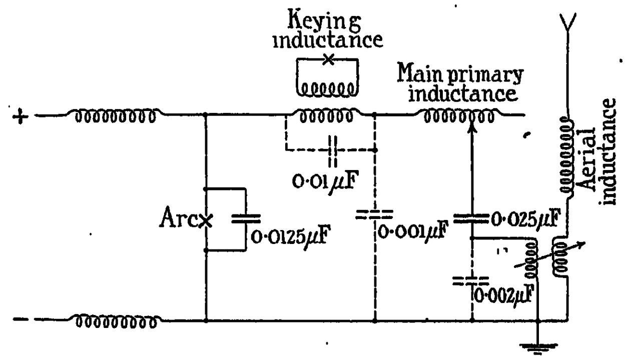

Fig. 14.—Diagram giving position of condensers (shown dotted) for shunting harmonics.

reduce the harmonics considerably, but these have not been adopted on account of the increase of mush. At Northolt, the extinction period being very short, the shunt condenser has only a small effect in stabilizing the frequency, and the damped-shunt condenser circuit is in use.

Damping circuits across the d.c. choke coils were also tried, but produced no improvement.

It was now thought that direct radiation from the primary circuit was the cause of disturbance in the immediate vicinity of the station, and steps were taken to screen the building. This was found to cause a considerable improvement locally.

By this time the only place which complained of disturbance on the broadcasting band was a town about 6 miles from Leafield, although places not so far away were immune. The telephone circuit from this town to the station was suspected and it was found that the heterodyne oscillator before mentioned, when held 2 ft. away from the switchboard in the telephone exchange at the town, could pick up the harmonics from Leafield. Steps were taken to place air-core choke coils of 2 000 μH inductance and 8 $\mu\mu$F self-capacity in the telephone and telegraph wires, and this

operation has quite removed the trouble in the town concerned, which is now quite clear of harmonics on the broadcasting band of wave-lengths.

It is rather curious how these high harmonics could get on to the telephone wires, because the circuits are in an underground cable for about a mile from the station. The cable sheath apparently carried harmonics, as the track of the cable across the field could be traced by walking across the route carrying the heterodyne oscillator. The choke coils were placed in the wires where they emerged from the cable and also at the point where they entered the adjacent town.

Section 7.

Keying of the Coupled Arc.

This is performed, as indicated in Fig. 14, by keying in the primary circuit only. The difference in frequency between spacing and marking is only 80 cycles per sec., so that the amplitude of secondary current is nearly the same in both cases. This constancy of amplitude avoids the considerable disturbance in the neighbourhood of the fundamental frequency which is present on systems employing a suppressed wave during spacing.

The authors have not attempted to give a complete bibliography covering the subject, as fairly extensive lists have already been given by Pedersen * and Elwell.†

They desire to thank Colonel Purves, the Engineer-in-Chief of the Post Office, for permission to publish the results of the experiments. They would also like to acknowledge the cordial co-operation and assistance of Mr. R. G. de Wardt, the engineer-in-charge of the Leafield station, who carried out many of the experimental tests and, in addition, specially devoted himself to the suppression of the residual harmonics.

* P. O. Pedersen: "The Poulsen Arc and its Theory," *Proceedings of the Institute of Radio Engineers*, 1917, vol. 5, p. 255.
† C. F. Elwell: "The Poulsen Arc Generator."

Discussion before the Wireless Section, 1 April, 1925.

Mr. C. F. Elwell: I am gratified to hear that the divided-wire inductance has been so successful and that the authors contemplate using divided wire in the variometer. It is interesting to know that a cheap form of insulation can be obtained by using ordinary dry whitewood, though I question whether this would be useful where divided wire is employed, as the corona effect from the small wires would probably cause burning to start. The apparatus for observing the frequency is ingenious, and the results obtained are very interesting. I do not think it is at all surprising that the condensers tend to stabilize the arc; that was the original object of putting a plain shunt condenser across the arc. The changes of frequency due to a variation in the quantity of methylated spirit fed to the arc are interesting. They rather point to the necessity for research along these lines. I should like the Post Office to try pure hydrogen, as it has many advantages.

Mr. R. V. Hansford: The average wireless engineer is apt to think that the arc is obsolete on account of the two great disadvantages which it possesses, viz. the emission of "mush" and the variation of frequency. By fitting a coupled circuit to the arc at Leafield and, by so doing, overcoming, to a very great extent, both those disadvantages, the authors have demonstrated quite successfully that the arc has been rescued from immediate obsolescence. I say "immediate" because I believe that ultimately the valve must take the first place. I do not think that there is much scope for the arc even now, except for aerial powers greater than 100 kW. I was responsible, in association with Mr. Faulkner, for the experiments at Stonehaven and the installation of the coupled arc at Northolt to which the authors refer. An experience such as that enables one to appreciate to the full the nature of the success at Leafield, and it is a source of satisfaction to know that the conclusions arrived at from our small efforts on small- and medium-power arcs have been confirmed in the repetition on a larger and more difficult scale at the high-power station at Leafield. The coupled arc at Northolt was not put in as a preliminary to Leafield, but as an absolute necessity. When the installation was started up for the contractor's acceptance tests it created such a stir amongst receivers in London that it was necessary to put a coupled circuit in before it could be used commercially. Messrs. Dubilier kindly supplied a temporary high-power condenser at very short notice, and the coupled circuit was in use commercially within a very few weeks. It seems to me that on two occasions in the paper the basis of the theory is given as an accepted fundamental principle which the average reader would not willingly accept without some explanation. In the early part of Section 2 the authors state: "It is known from theoretical principles that the efficiency of a coupled circuit is greater as the ratio of C_2/C_1 increases." I do not know that I could accept such a generalization as it stands. Theoretical considerations have led me to believe that as regards the use of a coupled circuit with a valve transmitter, the efficiency under ideal conditions is independent of the ratio of C_2/C_1; in practice, of course, the smaller the condenser the larger is the inductance and the larger the corresponding resistance losses and also, as the authors point out, the larger the voltage on the condenser; so that, in practice at any rate, there is a tendency to make C_2/C_1 as small as is reasonably possible, rather than large as suggested by the authors for an arc circuit. I can only conclude, therefore, that this expression in regard to efficiency applies to the arc in particular, and I think that point is worthy of a little more elaboration and justification. In the early part of Section 3 the authors state: "It is well known in this case that the frequency generated will be such that the net impedance of the primary circuit is zero." As a statement of principle I think that needs a little justification. Immediately afterwards the authors equate the reactance to zero, and, although they say on the next page that they have neglected resistance, I am not sure if they intended the sentence to read "net reactance" or "net impedance." Personally I

do not think that either statement would be strictly accurate.

Commander F. G. Loring: Although I have had nothing to do with the design of the Leafield station, I have had much to do with the results obtained, and they show, as I know from reports received, that an immense advance has been made during the past few years. Engineers in all parts of the world are interested in this Leafield experiment. I have been greatly struck by the amount of work involved in obtaining these results, not only as regards the maintenance of constant frequency in long-distance communication but also as regards the elimination of "mush" and harmonics. On the broadcasting band we used to receive a very large number of complaints. The complaints have not ceased, because a considerable body of listeners-in still blame Leafield and Northolt for any trouble that occurs in the broadcasting band. I am convinced, however, that those complaints are not now justified.

Mr. R. E. H. Carpenter: I should like to ask the authors their opinion as to the possible usefulness of a

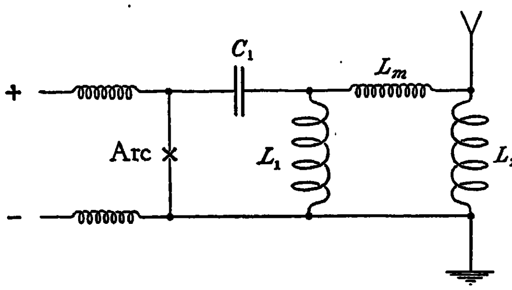

FIG. A.

method of coupling which is not referred to in the paper, and which I can explain more readily in diagrammatic form (see Fig. A). If a choke L_m of small self-capacity and high reactance were connected in the manner shown, it should give the desired advantage as regards the passage to the aerial circuit of the fundamental frequency, with increasing impedance for the harmonics. It is conceivable that that might form a cheap and convenient way of effecting the desired type of coupling. The three coils could be conveniently at right angles.

Mr. A. C. Warren: I should like to identify myself with Mr. Hansford's remarks on the efficiency of coupled circuits. I presume that in their statement on page 698 the authors intended to refer to the overall efficiency of the coupled arc, in which case the evidence is experimental rather than theoretical. Experiments at Northolt showed that the efficiency increased with the ratio C_2/C_1, as indicated in Table A.

TABLE A.

Method of working	C_2/C_1	Efficiency
		per cent
Coupled circuit	0·7	25
Coupled circuit	1·4	28
Coupled circuit	2·65	39
Plain aerial	—	34

In Section 5 the authors state that the frequency-changes due to circuit variations are halved by the use of the coupled circuit. At Leafield, under the working conditions the primary and secondary currents and circuit constants are approximately equal. Further, the second term in the equation for determining the frequency (page 703) may be rewritten $(I_2^2/I_1^2)X_2$; thus it seems to me that the compensation which occurs actually balances the variation, since I_2/I_1 is approximately unity for small circuit variations. This would account for the exceptional constancy of frequency obtained at Leafield.

Dr. W. H. Eccles: It would be very interesting if the authors would explain, briefly and in simple language, why an arc will maintain a coupled circuit in only one frequency. A coupled circuit has two natural frequencies and will, when sparked, give two wave-lengths simultaneously. If, however, it is put on an arc circuit, it will be excited in only one of these frequencies. Why is only one frequency excited by an arc at a time, and why does the arc sometimes prefer the shorter and sometimes the longer of the two wave-lengths? The mathematical explanations have, of course, been published; what I should like to hear is a physical one.

Mr. R. G. de Wardt (*communicated*): The coupled circuit at Leafield has now been in use for over 12 months, and testimony to the excellence of the design is given by the fact that although Leafield transmits on an average for 18 to 20 hours a day, on only one occasion has it been necessary to revert to plain aerial working. This was a few days after the coupled circuit had been brought into use and before the intricacies of tuning had been fully mastered, and was then only necessary to avoid delay in a transmission. The condenser design is the most novel feature of the circuit, and it will be of interest to members of this Institution to know that during tuning tests three of these condensers were operated at a potential of 90 000 volts at a frequency of 25 000 cycles per sec. for over an hour without any difficulty being experienced. A point which the authors do not mention is the sharpness of the emitted wave. I have received correspondence from all over the world relative to Leafield's transmissions, and the majority of the writers comment on the sharpness of the tuning. Leafield's 12 350-m wave is perhaps unfortunately situated in that it is close to the wave-lengths of several of the American high-power stations, together with Nauen and Stavanger, so that sharpness of the emitted wave is of importance. A correspondingly high degree of selectivity on the part of the receivers used to receive Leafield's signals is of course necessary if full advantage of this feature is to be taken. The constancy of the wave-length is, as the authors point out, a very important point, and an interesting commentary on this was furnished by the engineer in charge of the American station with which Leafield works traffic. He stated that the note of our signals gradually changed during a long transmission. Careful checks failed to find any drift in the frequency of the emitted wave, and this change in note appears to be due to the variation in heterodyne note of the receiver due to variation in

filament brilliancy. With regard to the elimination of mush on the broadcasting band in the near vicinity of the station, the screen over the building containing the arc transmitter and the primary and secondary circuits has, without doubt, been the most effective method of prevention. This screen only affected local listeners and had no effect on the mush in London, for example. Before this was adopted, the experiment of earthing the aerial at the lead-in, and energizing the primary circuit with full normal current, was tried. No difference in mush could be noticed at a distance of 2 miles. Fears were expressed that such a screen would cause heavy losses, but no appreciable difference can be noticed. Care was taken when erecting the screen in so selecting the earthing points that no one wire carried an abnormal current. This screen, which has now been up for some months, appears to be less effective than when first erected, probably owing to the fact that only dry joints were used, the screen being of an experimental nature. It is now being replaced by a permanent arrangement in which all joints will be soldered.

Major A. G. Lee and **Mr. A. J. Gill** (*in reply*): Mr. Elwell raises the question of the use of American whitewood as insulation for coils composed of divided wire. We have so far observed no trouble from corona, but in any case steps are ordinarily taken to design the coil to run below the corona limit. We agree with Mr. Elwell on the advantages of the use of pure hydrogen, and it is proposed to try it when a suitable opportunity occurs.

Mr. Hansford and Mr. Warren both suggest that the statement in regard to the dependence of the efficiency upon the ratio C_2/C_1 is not based on theoretical principles. They may perhaps be referred to the paper by Chaffee * on the amplitude relations in coupled circuits. He found that the ratio of I_2/I_1, for both higher and lower frequency oscillations, was proportional to $\sqrt{(C_2/C_1)}$, and we have verified this relationship to hold for the undamped free oscillations of the arc circuit. This amplitude ratio is unaffected by the resistance of the circuits unless the resistance is very large. The maximum circuit efficiency, apart from other considerations, is obtained by increasing the ratio of I_2/I_1 as much as possible, because resistance losses in the primary represent pure waste. As has been pointed out in the paper, voltage limitation in the condenser design is the principal determining factor in this direction. Mr. Warren's experimental results are of interest in corroborating the theoretical relationship.

Mr. Hansford also suggests a confusion between the terms "impedance" and "reactance" in connection with the remarks on the frequencies generated by the coupled circuit, and disputes the axiomatic nature of the principle that "the frequency generated will be such that the net impedance of the primary circuit is zero." This is such an old well-accepted principle that it is somewhat surprising to find it challenged at this date. The theorem has been well expounded by Kennelly † in a very interesting paper published in 1916, though, as was pointed out in the discussion on Kennelly's paper, the theorem was in use by Heaviside and Perry. From a physical point of view the statement is fairly obvious, because there is no physical alternating E.M.F. to drive the oscillating current which actually exists. As the sum of the alternating voltages round the circuit is zero, the net impedance must also be zero. The angular velocity of the oscillation will be such as to bring about this condition. It should be mentioned that the discontinuity in the arc cycle introduces an unknown factor into the question of frequency, which cannot be taken into account mathematically. The use of reactances, instead of impedances, in the equations in the paper is the usual approximate method of determining the frequency, and inasmuch as the negative resistance of the arc balances the positive resistance of the circuit, when taken over a complete cycle, the result is sufficiently accurate. The discontinuity in the arc cycle prevents the complete mathematical expression of the resistances (including negative resistance) in the circuit.

Mr. Carpenter's suggested coupling is interesting, and it is thought that the choke feed to the secondary circuit would be effective in reducing the transmission of harmonics. Without an actual trial it would be difficult to say whether it would work smoothly. In the f_1 type of oscillation the choke would carry only a few amperes, whilst in the f_2 oscillation it would have the full antenna current flowing through it, which would give rise to peculiar effects in regard to the tune of the circuit.

Mr. Warren suggests an explanation for the constancy of frequency at Leafield. As was pointed out above, I_2/I_1 is proportional to $\sqrt{(C_2/C_1)}$, hence it follows that the current ratio cannot remain constant for small circuit variations as suggested.

Mr. de Wardt's remarks on the screening of the building emphasize the necessity for preventing the primary circuit from emitting disturbances which will affect points in the near vicinity of the wireless station. It may be of interest to mention that recently at Northolt the same problem has been met in another way. The primary coil had a large number of spare turns which have been short-circuited by a condenser which tunes them to a point above the broadcasting band. Any harmonic current in the primary on the broadcasting band will then induce in the short-circuited turns harmonic current which is 180° out of phase with the harmonic current in the primary, thus producing a counter magnetic field, which for points outside the station cancels out the main field due to the primary. The condition for cancellation is that the harmonic ampere-turns in the short-circuit coil must equal the harmonic ampere-turns in the primary coil.

The question raised by Dr. Eccles is a difficult one to answer satisfactorily, because the answer is not capable of convincing proof. In the first place, as already suggested in the paper, the coupled arc appears to be capable of performing on only one frequency at a time, because of the effect of the discontinuity in the arc cycle. It is, perhaps, not generally realized that a system of two ordinary coupled circuits can be made to oscillate on only one frequency, by suitable arrange-

* E. L. Chaffee: "Amplitude Relations in Coupled Circuits," *Proceedings of the Institute of Radio Engineers*, 1916, vol. 4, p. 283.

† A. E. Kennelly: "The Impedances, Angular Velocities and Frequencies of Oscillating Current Circuits," *Proceedings of the Institute of Radio Engineers*, 1916, vol. 4, p. 47.

ments of the initial charges in the circuit (the experiment is easily demonstrated with two coupled pendulums). Such a system of oscillation is perfectly stable in the absence of any disturbing force. It would, however, be expected that such disturbing forces might be present in an arc circuit, but this is where the effect of the discontinuity in the arc cycle is felt. If we assume one type of oscillation to have been built up and then we introduce a disturbance which tends to set up the other type of oscillation, it is thought that the gap in the arc cycle—during which there is no current through the arc—would tend to choke out the building-up process of the second type of oscillation. A similar phenomenon is present in coupled-valve oscillation circuits, in which a heavy negative bias on the grid prevents more than one type of oscillation being maintained, the oscillation with the lower amplitude under the particular circuit conditions being eliminated. At the isochronous position it is found that the arc invariably comes up on the lower-frequency side. When the tuning is carried beyond the isochronous position, in the high-frequency direction, but below the point where the frequency discontinuity appears, and the arc is started up, the lower frequency is generated in about 75 per cent of the times, while in 25 per cent the arc comes up on the higher-frequency oscillation, which frequently reverts to the low side after running for a short time. These facts are difficult to explain; they seem to hold only for the inductive type of coupling and may even be individual to the particular circuit layout employed.

Mr. Hansford refers to the arc as having been rescued from immediate obsolescence. This is, however, a question of economics. The arc and valve are now on a par in regard to technical performance, except for the lower power efficiency of the arc. The future will therefore decide upon the relative running costs of the valve station, with its expensive maintenance, and the arc station with its low maintenance charges but higher power costs.

DISCUSSION ON "SOME ACOUSTIC EXPERIMENTS WITH TELEPHONE RECEIVERS." *

Mr. M. D. Hart (*communicated*): I should like to express my appreciation of the authors' method, given in Part I of the paper, for determining the natural frequency of a telephone diaphragm, but I wish to join issue with them on the subject of their measurement of "overall acoustical-electrical efficiency." From the figures given in Table 10 it would appear that the energy flux of the sounds which were used was as great as $22 \cdot 48$ ergs per cm^2 per second, and the measurement of these figures is based on the validity of the adiabatic law at the amplitudes encountered. I would point out that Rayleigh's figure for the amplitude of a just-audible sound of frequency 256 periods per sec. is $1 \cdot 27 \times 10^{-7}$ cm,† and from this figure the corresponding energy flux may be calculated as $8 \cdot 5 \times 10^{-7}$ ergs per cm^2 per second, using the expression $\frac{1}{2}\rho n^2 a^2 c$ for the energy flux.‡ Thus it seems that the energy flux of the sounds dealt with in the paper were of the order of tens of millions of times as great as that of the minimum audible sound, and the application of the adiabatic law, on the assumption of the correctness of which the authors' calculations are based, to such amplitudes is very improbable. Further, it has been shown § that, in the case of sounds of frequency 100, an energy flux of about 15×10^{-4} ergs per cm^2 per second involves quite an appreciable value of what is called the "degradation coefficient," showing that even for these amplitudes, which correspond to a fairly loud sound, the divergence from the adiabatic law may not be neglected. Moreover, it is shown in the last-mentioned paper that, when the values of the degradation coefficient are of the order of those investigated therein, a large fraction of the sound energy emitted from the source is degraded into heat in the atmosphere through which the sound passes, so that a measurement of efficiency based upon energy readings taken at an arbitrary distance from the source does not represent the true "acoustical-electrical" efficiency of the latter. To sum up: the values for the energy flux quoted in the paper are so enormous that the validity of the adiabatic law on which their calculation is based is very questionable and, even if they be correct, the figure given for the efficiency of the receiver does not truly represent that quantity and should be qualified by the distance from it at which the observations were taken in any particular case.

Dr. E. T. Paris (*communicated*): Experiments of the kind described in the paper are of great interest and importance to those concerned with acoustical measurements, and it is satisfactory to learn that a direct measurement of the acoustical-electrical efficiency of a telephone receiver can be made with, apparently, so little difficulty. In connection with these efficiency measurements, however, there is one point to which I think more attention should be paid. The method of measuring the acoustical energy flux described in the paper depends on the correctness of the equation given on page 512 for the particle velocity in a spherical sound-wave, and the experimental verification of this equation might well be extended in view of the fact that recent experiments have led us to expect an appreciable degradation of sound-energy in the neighbourhood of sources of quite moderate output. In view of my own experience with sound-absorbing materials, I was at first rather surprised to see that the 4 inches of cotton waste used by the authors to line the sound-chamber in which the experiments were performed was so effective as "to prevent any trouble from reflected waves." We have, at the Signals Experimental Establishment, Woolwich, apparatus by means of which the sound absorption-coefficient of any material can be readily measured, and it was thought that some observations on a 4-inch layer of loosely packed cotton waste, as used in the experiments, might be of interest to the authors. The result showed that this substance has a very high absorption coefficient, two measurements with sound of frequency 512 vibrations per second giving the values $0 \cdot 92$ and $0 \cdot 91$ respectively, the layer of cotton waste being backed by three layers of five-ply wood glued together. This means that over 90 per cent of the incident sound-energy is "absorbed" (i.e. not reflected), so that a surface which is covered with this material approximates to one which is acoustically "black." The method employed for measuring the absorption-coefficient was the "stationary-wave" method, in which use is made of the interference phenomena occurring between the incident sound-wave and that reflected from the specimen under test. Although over 90 per cent of the incident sound-energy was absorbed by the cotton waste, these interference phenomena were still quite well marked, and gave rise to positions of maximum and minimum pressure-variation in front of the specimen, such that the amplitude at a maximum was about $1 \cdot 8$ times that at a minimum. The experiments showing the effect of an air cavity on the frequency of a telephone diaphragm are especially interesting. It seems that it might be possible to employ the observed change in the fundamental frequency of a diaphragm due to an air cavity of known volume for the purpose of calculating the equivalent mass of the diaphragm. If the diaphragm is supposed to be replaced by a simple piston-like vibrator of mass m controlled by a mass-less spring of stiffness S, the calculation of the additional stiffness S' in terms of the volume of the air cavity and the area and mass of the piston does not appear to present any

* Paper by Prof. E. Mallett and Dr. G. F. Dutton (see page 502).
† Cf. Lord RAYLEIGH: "Theory of Sound," 1896, vol. 2, p. 439.
‡ Cf. HORACE LAMB: "The Dynamical Theory of Sound," 1910, p. 167.
§ M. D. HART: "On the Degradation of Acoustical Energy," *Proceedings of the Royal Society*, A, 1924, vol. 105, p. 82.

special difficulty, and it would be interesting to see how the equivalent mass determined in this way compares with that found by other means, such as loading the diaphragm, or the alternative method described by Kennelly in "Electrical Vibration Instruments," Chapter 10. The double-resonance phenomena observed when the air cavity is extended into a long tube (Table 5 and Fig. 12, p. 510) recall the effects observed with certain acoustical double resonators, the theory of which has been dealt with by the writer.* By an extension of the method employed in the papers referred to, an equation can be derived from which the resonance frequencies of a simple tube and diaphragm combination could be worked out, provided that we know the equivalent mass and area of the diaphragm. For a tube of length L and cross-sectional area σ_1, closed at one end by a rigid plate and at the other by a diaphragm of equivalent mass m and area σ_2, the resonance frequencies are those values of f which satisfy the equation

$$\cot \frac{2\pi f L}{a} = \frac{2\pi\sigma_1 m}{a\sigma_2^2\rho} f_0\left(\frac{f}{f_0} - \frac{f_0}{f}\right)$$

where f_0 is the resonance frequency of the diaphragm, a is the velocity of sound, and ρ is the density of air. This equation should be applicable, provided σ_2 is equal to or less than σ_1. In the actual experiment described by the authors, the cross-sectional area of the tube was considerably less than the area of the diaphragm, i.e. $\sigma_2 > \sigma_1$. In this case there is of necessity a widening of the tube at the diaphragm end and the matter is not so simple. I do not think that the combination can then be treated as a coupled system with only two components. The extra volume of air in the wider part of the tube will give rise to a third component, equivalent to a Helmholtz resonator interposed between the straight tube and the diaphragm. The combination is then straight tube—Helmholtz resonator—diaphragm, the end of the straight tube forming the neck, and the diaphragm part of the wall, of the Helmholtz resonator. If the combination is treated as a system with two components only (tube and diaphragm), and four times the length of the tube is taken as the wave-length appropriate to the tube component, we get the rather curious result that one of the resonance frequencies of the coupled system sometimes lies between the frequencies of the two components (see Table 5, p. 510, tube lengths 14·7 and 19·9 cm). The resonator and telephone combination shown in Fig. 14 should also show double-resonance phenomena. The arrangement is analogous to the "Boys resonator," the theory of which has been developed by the writer in the papers quoted above. The Boys resonator consists of a tube open at one end and leading at the other through a short neck into a Helmholtz resonator. The resonance frequencies of the Boys resonator are given by values of f which satisfy the equation

$$\tan \frac{2\pi f L}{a} = -\frac{2\pi\sigma_1}{ac} f_0\left(\frac{f}{f_0} - \frac{f_0}{f}\right)$$

L being the length and σ_1 the cross-sectional area of the tube, while c is the hydrodynamical conductance of the neck of the Helmholtz resonator and f_0 is its frequency. The Helmholtz resonator is equivalent to a simple vibrator of mass m, approximately equal to the mass of air in the neck. If the cross-sectional area of the neck is σ_2 and its length is l, this mass is $\rho\sigma_2 l$. Also, since the conductance c is approximately equal to σ_2/l, we have $c = \sigma_2/l = \rho\sigma_2^2/m$. Substituting this value of c in the frequency equation, we obtain

$$\tan \frac{2\pi f L}{a} = -\frac{2\pi\sigma_1 m}{a\sigma_2^2\rho} f_0\left(\frac{f}{f_0} - \frac{f_0}{f}\right)$$

and this will be the equation for determining the resonance frequencies of a double resonator made from a tube of length L and cross-sectional area σ_1, closed at one end by a diaphragm of equivalent mass m, area σ_2 and frequency f_0. This equation can, of course, be obtained quite independently of the theory of the Boys resonator, but the process is longer.

Prof. E. Mallett and Dr. G. F. Dutton (*in reply*): With regard to the "degradation of acoustical energy" and the applicability of the usual theory involving the adiabatic law, the authors' experiments do not confirm the results arrived at by Mr. Hart in his paper. The energy fluxes used in their experiments were very much greater than those used by Mr. Hart, and yet there was no indication of any "degradation." Table 7, for instance, shows that the variation of sound pressure and particle velocity at a frequency of 694 with radial distance from the equivalent source to be very closely in agreement with the usual theory, and Figs. 18 and 18 (*a*) give a similar result for a frequency of 439. These are not isolated results. Many other determinations agreed equally well. Two, at frequencies of 960 and 590, are illustrated in Fig. A. In all these cases the relation between

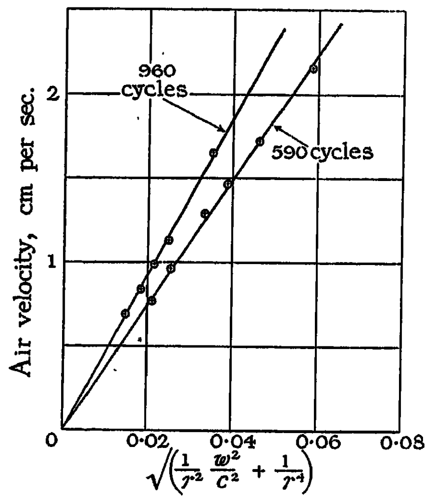

FIG. A.

$$\sqrt{\left(\frac{1}{r^2}\cdot\frac{\omega^2}{c^2} + \frac{1}{r^4}\right)}$$

and the particle velocity is seen to be represented by a straight line passing through the origin; whereas if

* *Proceedings of the Royal Society*, 1922, vol. 101, p. 301, and *Philosophical Magazine*, 1924, vol. 48, p. 769.

there were "degradation" of the order found by Mr. Hart the curves would be quite noticeably concave towards the abscissa. Again, Fig. 15 shows the relation between the exciting current of the telephone in the resonating tube and the particle velocity a few centimetres in front of the mouth. The fact that this is a straight line also indicates that up to a particle velocity of 4 cm per sec. at any rate there is no "degradation." For if any appreciable loss—increasing with amplitude—were taking place, either in the stationary wave within the tube or in the progressive wave outside, the rate of increase of particle velocity with exciting current would decrease as the latter was increased, and the curve would be concave towards the abscissa. Further, the various resonance curves of the telephone diaphragm taken by the Rayleigh disc would all have shown a flattening had marked losses been taking place in the

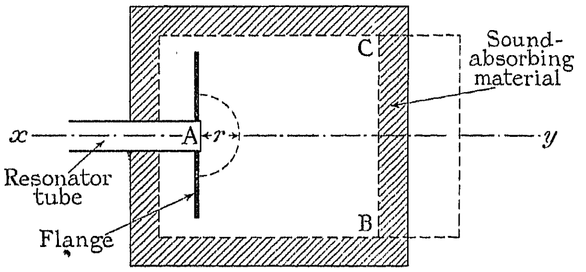

FIG. B.

sound wave, and such distortion would have been brought to light by the circle and straight-line construction. It appears, therefore, that at fluxes considerably greater than those used in the receiver efficiency determinations, and very considerably greater than those used by Mr. Hart, any "degradation" effect is negligibly small.

The measurements made by Dr. Paris on the sound-absorbing properties of cotton waste are very interesting and justify the authors' choice of this material for a lining for their sound chambers. The statement that no trouble was experienced from reflected waves refers of course to the measurements made, all within, say, 10 cm from the source of sound. In Fig. B, A represents the source of sound, xy the axis along which measurements were taken and CB the end wall of the box. Assume that the whole of the energy falls on CB, area 10 000 cm^2, and is reflected as a plane wave, and that measurements are being made 10 cm from A. Then taking Dr. Paris's figure of 91 per cent absorption the ratio of the reflected energy flux per cm^2 at A to the direct energy flux is $(2\pi r^2/10\,000) \times 0{\cdot}09$, or less than 0·6 per cent. When the distance from the source is 4 cm, as in the efficiency measurements, the ratio is 0·1 per cent. Actually, of course, the whole of the wave is not reflected direct from the end wall, but much of it strikes the other walls before reaching the area where measurements are being made, and at each reflection a further 91 per cent of the remaining energy is lost. The whole effect of reflection can therefore be neglected in the absence of resonance effects and standing waves, which at particular frequencies may give a little trouble. But even this may be avoided by a suitable choice of the positions of the apparatus within the box.

The authors did attempt to use the alteration of resonant frequency with alteration of cavity volume as a means of finding the equivalent mass. The problem reduces itself to finding the constant A in the equation $f_0^2 = \frac{1}{4\pi^2}\left\{\frac{S}{m} + \frac{A}{vm}\right\}$ at the top of page 508. For the slope of the curve of Fig. 9 is $A/(4\pi^2 m)$ and, if A is known, the equivalent mass m is found at once. Doubtless A could be determined mathematically, but then it would be necessary to assume that the diaphragm was vibrating according to the Bessel function theory. Or it might be determined from a static test, from measurements of the deflection at the centre with a given air pressure, but this would not be so simple as Kennelly's method of measuring the vibration amplitude at the centre at resonance.

Dr. Paris's remarks regarding the double-resonance curves are very interesting, and should help considerably towards a complete understanding of this complicated phenomenon. One of the objects of this series of experiments was to show that a diaphragm vibrating in any other mode than the fundamental was not coupled with the tube, and this was successfully demonstrated. That there actually are three members of the system, viz. diaphragm, cavity and tube, is clear, but the cavity is so far from its resonance that it can possibly be taken as merely modifying either or both of the other members, reducing the system in effect to one of two components.

PROCEEDINGS OF THE INSTITUTION.

43RD MEETING OF THE WIRELESS SECTION, 4 FEBRUARY, 1925.

(Held in the Institution Lecture Theatre.)

Mr. E. H. Shaughnessy, O.B.E., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 7th January, 1925, were taken as read and were confirmed and signed.

A paper by Messrs. L. B. Turner, Member, and F. P. Best, Student, entitled "The Optimum Damping in the Auditive Reception of Wireless Telegraph Signals" (see page 493), was read and discussed.

On the motion of the Chairman a hearty vote of thanks was accorded to the authors, and the meeting terminated at 7.22 p.m.

725TH ORDINARY MEETING, 5 FEBRUARY, 1925.

(Held in the Institution Lecture Theatre.)

Mr. W. B. Woodhouse, President, took the chair at 6 p.m., and announced that since the last meeting the Institution had lost two distinguished members, Mr. C. H. Wordingham, C.B.E., Past-President, and Mr. Oliver Heaviside, F.R.S., Honorary Member and Faraday Medallist. Votes of condolence with the families of the deceased were carried, the members standing in silence.

The minutes of the Ordinary Meeting of the 22nd January, 1925, were taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

A list of donations to the Benevolent Fund (see page 237) was also taken as read and the thanks of the meeting were accorded to the donors.

The President announced the presentation by Colonel R. K. Morcom of a statuette of the late Sir Joseph Wilson Swan, President of the Institution in 1898, and asked Dr. Ferranti to make a few remarks regarding the work of Sir Joseph Swan in connection with the development of electricity.

Dr. S. Z. de Ferranti: There are not so many now who were personally acquainted with Sir Joseph Swan. I had the privilege of discussing with him many things which interested him particularly, and especially the question of electric lighting, and I think that perhaps it is owing to this acquaintanceship—indeed, this friendship—that I have been asked to speak. I cannot, however, say anything adequate to the occasion, because to give in a few minutes a description of the work done by this great inventor would be out of the question. I should, however, like to remind the members that it is owing to him that we have electric lighting as we know it, and upon his work the present electrical industry has been built up, because the first of these heavy electrical engineering sections was electric lighting. Electric power, tramways, heating, and electro-metallurgy, have all followed on the electric light work which, as I say, commenced this great new development. Swan was seeking a means of producing electric light other than the arc lamp, and eventually succeeded in making the incandescent electric lamp very much as we know it to-day. The inventions of Edison have often been mentioned in this connection, but it is clear that Swan, quite independently, invented for all practical purposes the incandescent electric lamp, maybe at the same time as, or maybe sooner than, Edison. He was a wonderful inventor. He gathered together all known information on a subject and laboriously worked at it until he had got the idea into a shape in which it was useful. His idea of squirting incandescent lamp filaments was really the basis of what is becoming an important industry—the making of artificial silk. He did not pursue it to its full length of application to the silk industry, but nevertheless his original work made this further development possible. The statuette which has been offered to the Institution by Colonel Morcom is the work of Sir Joseph Swan's daughter, Mrs. Morcom, and I feel that if only Sir Joseph could have seen what has eventuated he would have been very delighted.

After some brief remarks by **Colonel R. K. Morcom,** the statuette was formally accepted by the President on behalf of the Institution.

Dr. J. H. Jeans, M.A., LL.D., Secretary of the Royal Society, then delivered the Sixteenth Kelvin Lecture entitled "Electrical Forces and Quanta" (see page 483).

Sir Oliver Lodge: Before proposing a vote of thanks to Mr. Jeans for his interesting lecture, I should like to take this opportunity of thanking the Council for the signal honour that they have done me this year in electing me an Honorary Member of the Institution. I appreciate it very much, because I have no claim to be called an engineer. I do not know that Mr. Jeans has been as revolutionary as I half expected him to be. He seems to disbelieve in an ether; but if he only means that he disbelieves in two ethers I agree with him. I say that we must have one; he is satisfied with none because he is a mathematician and can proceed and calculate without reference to it. I venture to say that the theories of relativity and of quanta do not explain—and do not really pretend to

explain—but they express the facts of nature in a wonderful manner, and I fully accept them as methods. When Mr. Jeans objects to the ether, he means, I venture to say, the old dynamic ether—the ether of Lord Kelvin. He, and Fitzgerald and others of the last century, were always trying to make a model of the ether, or, in other words, to explain or express the ether in terms of matter; and I think with Mr. Jeans that it cannot be done. We need not be surprised at this, for of the two things, ether and matter, ether is the more fundamental. One cannot explain the more fundamental in terms of the derived; and we know that matter is a derived thing. It is made up of electric charges, and therefore—doubtless, I say—made up of ether. Very well, one must explain electricity and matter in terms of ether, and start fundamentally; but we know too little about it. I hope, myself, that the ether will finally be explained hydro-dynamically—by some particular kind of circulatory motion. Such an explanation may be called dynamical in a sense, but one cannot exactly apply the ordinary methods. Meanwhile, for mathematical purposes, the ether can be ignored. Ignoring a thing does not put it out of existence. Those equations on the board—the whole of the relativity theory—never mention the ether at all; and they need not do so, of course. But when proceeding from equations to things themselves, to reality—whatever people mean by reality, it is a difficult term to define—then the ether—*an* ether—is necessary. I believe Einstein thinks so; and Eddington has told me that he thinks so. I am not at all sure what Mr. Jeans thinks, but he has a very great right to any opinion that he forms, because I yield to no one in admiration of his extraordinary mathematical powers. What he told us in the first part of the lecture was a masterly exposition of the essential points; his identification of Lord Kelvin's two overshadowing "clouds" is most interesting, and all he has said is instructive. The permanence of the universe, and the fact that it has lasted more than a millionth of a second, or a million seconds, does seem to depend on the facts which the theory of quanta strives to express. The connection between radiation energy and frequency is a great discovery, and a surprising one to me. It is not at all surprising that frequency remains constant;—we are familiar with that in the case of sound; sound travels from a concert room through wood or any sort of material, the wave-length changes enormously, but the pitch is preserved and the concert is just as good;—but that the electron-expelling energy is preserved is wonderful. Apparent continuity arising out of discontinuity is common: the pressure of the air appears to be quite continuous—the barometer shows this—but it is really due to a bombardment of separate particles. Our senses do not appreciate minutiæ, atomic minutiæ; and now that we are penetrating into the interior of the atom, we find things that we had not expected. We find the quantum active in the connection between ether and matter, and there is still a great deal to discover about that. I beg to propose that a hearty vote of thanks be accorded to Mr. Jeans for his extremely interesting lecture.

The resolution, after being seconded by **Dr. A. Russell, F.R.S.,** was put to the meeting by the President and carried unanimously.

The meeting terminated at 7.30 p.m.

726TH ORDINARY MEETING, 19 FEBRUARY, 1925.

(Held in the Institution Lecture Theatre.)

Mr. W. B. Woodhouse, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 5th February, 1925, were taken as read and were confirmed and signed.

Messrs. J. N. Robertson and H. Tomlinson Lee were appointed scrutineers of the ballot for the election and transfer of members, and, at the end of the meeting, the result of the ballot was declared as follows:—

Elections.

Associate Members.

Crivelli, Rene Gabriel, M.E.E.
Dunham, David, B.Sc. (Eng.)
Loveridge, Claude Warren, B.A.
Sparkes, Thomas.

Graduates.

Barkwith, Joseph William B.
Barry, Gerald Noel F.
Berry, Edgar.
Cullinan, Reginald.
Everett, Reginald Edgar.
Gardner, Ernest John.
Henn, Stanley Thomas.
Hortop, Cecil Lawrence.
Ince, Thomas Henry.

Graduates—continued.

Macdonald, James Wright.
Murphy, John.
Rao, N. Srinivas.
Troup, George.
Tubb, Burton Henry J.
Watson, Gerald Victor.
Webster, Harold.

Students.

Aitken, Thomas Archibald, B.Sc.
Allaway, Lionel George.
Bancroft, George Denton.
Baveja, Pran Nath.
Bayne, Alec Edward.
Bennett, James.
Black, Richard Henry.
Bone, Ronald Scoble.
Brown, James Duncan, B.A.
Buckingham, Donald.
Carlton, Cyril Gordon.
Chaplin, Stephen.
Chilton, George William.
Clarke, Harold.
Cobbold, Robert James.
Cocks, Sidney Herbert.
Crombleholme, Frederick.
Cunningham, Alastair Andrew.
Desai, Maganbhai Vaghjibhai.
Donegan, Jeremiah.
Dowsett, Harry Lyttleton.
Drummond, John Fleming.
Dunn, Philip Ryland.
Evans, Moses.

Students—continued.

Farmer, Frank.
Fouracre, Victor William M.
Ganly, Richard Ernest.
Gardner, Frank Joseph.
Glenn, Hugh.
Gray, John.
Guthrie, James Robert.
Haggart, Andrew.
Harris, Richard Norman.
Hockney, Thomas Reginald.
Hodge, Archibald Greig.
Holder, John Eric D.
Hoskin, Frank.
Hutchison, Eustace Neville.
Johnson, Kenneth Corbridge.
Kellas, James Macnicol.
Landale, Stenard Ernest A.
Lawrence, Walter Francis C.
Lawrence, Cecil Frederick.
Lyons, Douglas Arthur.
McGreevy, Thomas.
Mackay, Victor Peterson.
Marryat, John.
Meeke, James Denis.
Mepsted, Maurice Eustace.
Millward, Gerald Richard.
Myers, Clifford.
Myers, Leonard Morris.
Murdoch, Matthew Weir H.
Nunn, Richard Trevett.
Padwick, Henry Francis J.
Parsonage, John Frank.
Patmore, Sydney John.
Peel, George Neville.
Pike, Ralph Charles.
Reed, Edward James.
Rennie, Douglas Ogilvie.
Roebuck, Ronald.
Sandy, Vivian John S.
Simpson, Alexander Victor.
Smyth, Vere Stainer W.
Stewart, Charles Eric.
Stewart, Donald Arnott.
Stirrup, Reginald Brade C.
Swift, Edgar.
Tanner, Ernest Basil T.
Taylor, Arthur Harold.
Thomas, Eugene Royston.
Tracey, William Thomas.
Upton, Robert Hildyard.
Viant, John Robert.

TRANSFERS.

Associate Member to Member.

Amberton, Richard.
Collins, Albert, B.Sc.(Eng.).
East, Alan Neville.
James, William Henry N.
Lee, John Andrew.
Maxwell, Kenneth Graeme, Lieut.-Col., M.C.
Phillips, Charles Francis.

Graduate to Associate Member.

Brierley, Herbert.
Jamieson, James, B.Sc.

Student to Graduate.

Allsop, George, M.Eng.
Barrand, Percy Christian.
Base, George Cecil.
Bridgeman, Wilfrid Robert O.
Brough, Leonard George.
Cohen, Isaac Judah, B.Sc.(Eng.).
Cooper, George.
Cuffley, Walter.
Dunn, Charles Trevor, B.Sc.(Eng.).
Everett, Arthur G.
Graham, Alexander.
Harley, Lawrence Shepheard, B.Sc.(Eng.).
Harlow, Harold George, B.Sc.
Holman, Horace.
Howard, Arthur.
Jones, Ernest Thomas L.
Lash, Alfred Reeves.
McCulloch, Reginald Andrew.
Sinclair, William.
White, Albert Ernest.

A paper by Major E. Ivor David, Member, entitled "Electricity in Mines" (see page 521), was read and discussed. On the motion of the President a vote of thanks to the author was carried with acclamation, and the meeting terminated at 7.50 p.m.

44TH MEETING OF THE WIRELESS SECTION, 4 MARCH, 1925.

(Held in the Institution Lecture Theatre.)

Mr. E. H. Shaughnessy, O.B.E., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 4th February, 1925, were taken as read and were confirmed and signed.

A paper by Mr. D. W. Dye, B.Sc., Associate Member, entitled "Current-Transformer Methods of Producing Small, Known Voltages and Currents at Radio Frequencies for Calibrating Purposes" (see page 597), and a paper by Lieut.-Colonel K. E. Edgeworth, D.S.O., M.C., and Mr. G. W. N. Cobbold, M.A., Associate Member, entitled "The Measurement of Frequency and Allied Quantities in Wireless Telegraphy," were read and discussed.

Mr. G. W. N. Cobbold also demonstrated "A Direct Method of Setting an Undamped Radio Oscillator to any Desired Frequency Within an Accuracy Approaching 1 in 10 000," and this was discussed.

On the motion of the Chairman votes of thanks to the authors for their papers and to Mr. Cobbold for his demonstration were carried with acclamation, and the meeting terminated at 7.55 p.m.

727TH ORDINARY MEETING, 5 MARCH, 1925.

(Held in the Institution Lecture Theatre.)

Mr. W. B. Woodhouse, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 19th February, 1925, were taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

A list of donations to the Benevolent Fund (see page 334) was taken as read and the thanks of the meeting were accorded to the donors.

A paper by Colonel T. F. Purves, O.B.E., Member, entitled "The Post Office and Automatic Telephones" (see page 617), was read and discussed. On the motion of the President a vote of thanks to the author was carried with acclamation, and the meeting terminated at 7.55 p.m.

INSTITUTION NOTES.

Nominations for Election to the Council.

In addition to those members nominated by the Council (see page 613) the following have been nominated for the vacancies which will occur on the 30th September next:—

Ordinary Members of Council (Members):

C. Rodgers, O.B.E., B.Sc. (*Nominated by* Messrs. A. R. Everest, A. B. Field, M.A., B.Sc., A. P. M. Fleming, C.B.E., M.Sc., F. C. Gibbons, F. Hird, B.A., E. S. New, M. J. Railing, W. O. Smith, F. Wallis and A. P. Wood).

J. N. Waite (*Nominated by* Messrs. J. Anderson, L. H. A. Carr, M.Sc.Tech., J. F. Crowley, D.Sc., E. Fawssett, R. Johnson, A. H. W. Marshall, W. M. Selvey, C. Vernier, E. B. Wedmore and J. Wright).

Ordinary Member of Council (Associate Member):

J. H. Parker (*Nominated by* Messrs. W. F. Andrews, E. B. Barnett, B. B. Heaviside, W. J. Jeffery, A. L. Lunn, A. P. MacAlister, T. A. G. Margary, W. J. Oswald, L. Owen and W. Young).

Associate Membership Examination Results.

April 1925, Supplementary List.*

Passed.

Hallé, C. R. (South Africa).
Larkin, C. N. (South Africa).

Students' Premiums.

The following premiums, each of the value of £10, have been awarded by the Council for papers read before the Students' Sections during the past session:—

Author	*Title of Paper*	*Students' Section*
P. G. Ashley, B.Sc.	"Fuses and Fusible Cut-outs"	North-Eastern
D. I. Dawbarn	"Variable-Speed Three-Phase Commutator Motors"	North-Eastern
E. Gallizia	"Some Problems of the Turbo-Alternator"	South Midland
J. H. Reyner	"The Direction-finding Equipment at Niton and Cullercoats"	London
W. R. T. Skinner, B.Sc., and G. E. Barrett, B.Sc.Tech.	"High-Pressure and High-Temperature Steam"	North Midland
A. Tustin, M.Sc.	"Economics and Industrial Electrification"	North-Western

* See page 614.

Model Form of General Conditions of Contract (Export).

The two following additional sets of Model Conditions of Contract have been approved by the Council:—

B1. Export Contracts (delivery f.o.b.; excluding cables).

B2. Export Contracts (including complete erection or supervision of erection; excluding cables).

Copies of each may be obtained from the Secretary of the Institution, Savoy Place, Victoria Embankment, London, W.C. 2., or from the publishers, Messrs. E. and F. N. Spon, Ltd., 57, Haymarket, London, S.W. 1, at one shilling per copy, post free.

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 May–25 June, 1925:—

	£	s.	d.
Adcock, F. W. D. (Leigh-on-Sea)		5	0
Allan, C. T. T. (Cardiff)	2	2	0
Aylott, H. J. (Ilford)		10	0*
Barclay, W. R. (Birmingham)		5	0*
Barnes, C. W. (London)		5	0
Beale, H. R. (Wellington, N.Z.)		8	6
Beck, J. W. (Seven Kings)		5	0
Bellamy, L. C. F. (Hong-Kong)	1	1	0
Cameron, D. L. (Toronto)		16	0
Campbell, R. G. (Liverpool)		10	0
Cleaver, R. L. (London)		15	0
Clinch, W. N. C. (Brimsdown)		5	0
Coe, G. D. (Wrexham)		10	6
Colborn, C. (Swansea)		8	6
Collins, W. (Bristol)	1	1	0
Coventon, G. L. (Chepstow)		5	0
Crocker, E. (Birmingham)		5	0*
Damsell, R. F. (Rugby)		5	0*
De Lattre, M. (Coventry)		10	6*
Dent, L. B. (London)		5	0
Dinham-Peren, A. E. H. (London)		5	0
Donovan, E. T. G. (Birmingham)		6	0
Edgar, F. J. (London)		10	0
Electrical Engineers' Ball Committee (per A. M. Sillar)	70	0	0
Elliott, F. F. (London)		10	0
Evans, G. J. (Pontypridd)		2	6
Everest, A. R. (Rugby)		10	6*
Forrest, F. (Birmingham)		10	6*
Fry, C. E. (Birmingham)		2	6
Galloway, J. (Calcutta)		7	0

* Annual Subscriptions.

	£.	s.	d.
Hall, F. C. (Birmingham)	5	0	0
Gerrard, F. J. (London)		5	0
Glass, C. G. (Llanelly)		10	0
Grainge, J. R. W. (London)		5	0
Haward, F. N. (London)		10	0
Hayhurst, H. (Sheffield)		5	0
Hazel, H. C. (Liverpool)		10	0
Homan, F. T. (Calcutta)		10	6*
Howell, A. (West Bromwich)		5	0
Jarratt, A. (Swansea)		5	0
Jones, J. R. (Houghton-le-Spring)		5	0
Joseph, S. (Liverpool)		2	6
Kelman, W. H. M. (London)		5	0
Kempster, J. W. (Port Glasgow)	1	1	0
King, W. H. (Canterbury, N.Z.)		5	0
Lea, J. T. (Manchester)		5	0
Lewis, T. E. (Cardiff)		5	0
Lingard, J. (Leith)		5	0
Marchant, Dr. E. W. (Liverpool)	1	0	0
Minton, R. C. (East Boldon, Co. Durham)		5	0*
Mitchell, G. W. (Hull)		5	0
Murray, A. R. (London)		10	6
Nelson, T. J. (Pyle, Glam.)		5	0
Newman, A. J. (Bristol)	1	1	0*
Nicolson, G. (Weymouth)		5	0
Oughton, F. C. (West Bridgford)		5	0*
Pearce, J. G. (Birmingham)		5	0
Pennington, W. (London)		5	0
Pike, F. A. (London)		5	0
Pratt, L. H. (Newcastle-on-Tyne)		5	0
Record, J. W. (Bowden)		10	0
Redman, R. H. (Dewsbury)		10	0
Rigg, R. (London)		5	0
Romain, W. A. B. (London)		5	0
Samuel, H. P. (West Bromwich)		5	0
Scott, G. I. (Wells)		5	0
Scott, G. J. D. (London)		10	6
Sexton, F. P. (Teddington)		5	0*
Sharp, H. P. (London)		3	6
Sheldon, R. A. (Birmingham)		5	0*
Simpson, A. A. (Birmingham)		2	6*
Summer Meeting, collection at	1	15	0
Tackley, A. L. (Birmingham)		5	0
Troughton, J. A. (Bournemouth)		5	0
Walker, F. (Sale, Cheshire)		5	0
Wallace, M. H. (Hong-Kong)		8	6
Walsh, E. J. (Musselburgh)		10	0*
Wilkinson, H. W. (London)		10	0
Williams, J. W. (Wrexham)		5	0
Williamson, G. E. E. (Littleover, Derby)		5	0*
Willson, L. F. (London)		3	6
Wood, L. E. (Bradford)		5	0
Young, James (Birmingham)		5	0*

* Annual Subscriptions.

Accessions to the Reference Library.

AGUINO, L. D'. La decomposizione delle righe spettrali per effetto del campo elettrico.
8vo. 86 pp. *Napoli*, 1921

AITKEN, W. An outline of automatic telephony.
sm. 8vo. 143 pp. *London*, 1925

AMERICAN BUREAU OF ENGINEERING, INC. The automobile storage battery: its care and repair.
8vo. 284 pp. *Chicago*, [1918]

ANDERSON, R. J. The metallurgy of aluminium and aluminium alloys. 8vo. 944 pp. *New York*, 1925

ANNETT, F. A., and ROE, A. C. Connecting and testing direct-current machines.
8vo. 247 pp. *New York*, 1925

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PERMANENT MAGNETS IN THEORY AND PRACTICE.

(SECOND PAPER.)*

By S. EVERSHED, Member.

(*Paper received 4th February, and read before* THE INSTITUTION *19th March,* 1925.)

PREFACE.

The present paper follows one on the same subject read before the Institution on the 13th May, 1920. It was originally intended that modern practice in magnet-making should be described in a second paper, with enough metallurgical explanation to render the various processes intelligible. This simple plan was soon abandoned when it was discovered that current metallurgical science had nothing to say about those matters which are of most consequence to the magnet maker. His perplexities begin with the steel itself as it comes from the steelworks. Why should magnets made from one batch of steel differ so widely in their magnetic power? What is the source of the magnetic potency of steel? And what causes the strength of a permanent magnet to fall off with age? To answer such questions as these, the present writer found it necessary to enter an almost untrodden metallurgical field; to study spoiled magnet steel and its restoration; to determine the relation between the carbon content and the coercive force of hardened tungsten steel; to investigate the harmful magnetic effect of ultra-heating; and, lastly, to measure the slow decay of hardened steel.

The outcome of prolonged research on these and other kindred subjects is included in the following paper in Part III, which treats the metallurgy of magnet steel as a material for permanent magnets, and is founded on the hypothesis that the potency of steel arises from the molecular pattern created by the solution of carbon compounds in magnetic iron. A strictly logical sequence in so intricate a subject is out of the question, but for greater ease of reading the various matters to be dealt with are presented, so far as possible, in their natural order. No attempt has been made to adhere to conventional metallurgical ideas or phraseology. The metallurgical reader, should there chance to be one, may possibly feel lost without his pearlite, his austenite, and his phase rule, but a little fresh air does no one any harm.

Part IV opens with a general account of the manufacture of permanent magnets, beginning with the making of the steel. The different stages of manufacture are then dealt with, one after the other, attention being mainly directed to points of difficulty and matters in which common practice stands in need of amendment. It is shown that the most favourable composition for magnet steel can be determined once for all from measurements of available magnetic energy, the optimum composition of tungsten magnet steel having already been ascertained by that means.

The section in Part IV under the heading "Cast Magnets" contains an account of a research conducted by the British Scientific Instrument Research Association, and completed some three years since. It was found possible to cast permanent magnets in either tungsten steel or cobalt steel, and the cast magnets, while presenting many advantages over the customary magnets of rolled steel, were in no way inferior to them in magnetic power.

Throughout the paper, and notably in bringing Part IV to a conclusion, the author has freely introduced ideas of a speculative kind. This has been done rather in the hope that trains of thought may be set going in other minds in altogether novel directions. Where these will end no one can tell. Perhaps nowhere; but in any case it is good to make occasional excursions from our accustomed groove.

In the earlier stages of research the want of suitable apparatus made it difficult to proceed without metallurgical help. This was invariably forthcoming, and at the very beginning the author was able, by kind permission, to make certain preliminary experiments in the works of the Birmingham Small Arms Co. Thanks are also due to the directors of Messrs. W. H. Allen and Son of Bedford for permission to use the "inverse rate curve" apparatus installed in their metallurgical laboratory, and to Mr. R. Rolfe, who very kindly undertook the task of determining inverse rate curves from samples of tungsten magnet steel supplied by the author's firm.

The numerous samples of tungsten steel with graded carbon content, required for the determination of the carbon-coercive-force curve, were all specially cast and presented to the author by Messrs. Thos. Firth and Sons, and his warmest thanks are due to the directors of the firm for this most generous help, as also to Dr. W. H. Hatfield, the director of the Brown-Firth Research Laboratory, under whose supervision the samples were prepared.

All the chemical analyses given in the paper were made for the author's firm by Messrs. Riley, Harbord and Law, and the writer is indebted both to Mr. Harbord and to Mr. Law for helpful advice on many occasions. Thanks are specially due to Mr. Law for the microphotographs of tungsten magnet steel referred to in the introduction to Part III.

Nearly all the experimental work recorded in the paper was done by Mr. Finnis, ably assisted by

* See *Journal I.E.E.*, 1920, vol. 58, p. 780.

Mr. Baker. It has been the author's pleasure on more than one occasion in past years to acknowledge his indebtedness to Mr. Finnis. On the present occasion the two graphs given in Figs. 2 and 3 will serve better than any words as testimony of the skill and precision with which the experimental work was done. In plotting these curves for reproduction the author has purposely included every observational point just as it stands in the original record of the experiments, each plotted point standing for the simultaneous readings of temperature and magnetic intensity by two observers.

Finally, a word as to standards of measurement. Temperatures have almost invariably been measured by platinum-rhodium-platinum thermo-couples made in the laboratory from wires supplied by Messrs. Johnson and Mathey, the couples being subsequently verified by the National Physical Laboratory. Occasional use has been made of a Leeds and Northrup colour-comparison pyrometer in cases where it was impracticable to insert a thermo-couple inside the steel test-piece. The author's astatic moving-coil magnetometer has been used throughout for the magnetic tests. The instrument is standardized by comparison with standard inductance coils which have been verified by the National Physical Laboratory.

Except where another source is indicated, the experimental work recorded in the diagrams and tables in this paper was done at Acton Lane Works under the author's supervision.

Table of Contents.

PART III.

THE METALLURGY OF THE PERMANENT MAGNET.

(1) Introduction.

Natural phenomena being mostly beyond human comprehension, we often try to explain them to ourselves by analogy with something simpler. But simplification and explanation seldom go well together. There is frequently an illusive simplicity in the form in which Nature presents her puzzles, and then the first step in explanation is apt to land the inquirer in a maze of difficulty.

So it is with the steel of which a permanent magnet is made. Solid and hard, a rigid body with a definite shape, it presents no obvious difficulty to the mind and apparently nothing could very well be simpler. But metallurgy tells a very different tale. Steel is found to possess an extremely complicated structure and to be endowed with many strange properties. Magnetism tells much the same story of complexity, but in another language. Among the more mysterious attributes of steel is the property with which we are concerned in this paper, namely, the power of maintaining a magnetic field and acting as a permanent magnet. It might be supposed that somewhere in the long and intricate metallurgical story of steel, as told in many a textbook, this occult magnetic power would find a place if not an explanation. It is not so, however, and just in those places where it is natural to look for something relating to the properties of steel which give rise to the two factors of magnetic energy, we find gaps in the story. But both metallurgical structure and inherent magnetism go to the making of a permanent magnet, and in the present paper an attempt must be made to fill up the gaps as far as possible and present the story of magnetized steel as a whole. For reasons of space it can only be a story in outline, and on the metallurgical side it will naturally be confined to steels of the composition used for magnets.

The absence of metallurgical guidance in matters

concerning the magnetism of steel is natural enough. Steel is mainly employed for structural purposes where mechanical strength is the first consideration, and for that reason metallurgical research has been directed for the most part to the mechanical properties of the various kinds of steel; properties which are largely governed by chemical composition, thermal treatment and crystalline structure. Hence in the past the principal weapons of the metallurgist have been chemical analysis, the pyrometer, and the microscope, and it could hardly be expected that these would throw light on magnetic phenomena which appear to have their origin in the actions of individual atoms and molecules.

In a recent paper * Mr. Watson has sought to establish some connection between the gross structure seen in the microscope, and the magnetic properties of magnet steel. It is only natural that they should have something to do with each other, but the relation cannot be that of cause and effect. Anyone who makes a microscopic examination of the interior of a permanent magnet under a high magnifying power, can scarcely fail to be struck by the fact that the more powerful the magnet the less there is to be seen in the microscope. The harder the steel the fewer the signs of crystalline or other structure, and inside a magnet made of good homogeneous magnet steel in the completely hardened state there is scarcely a trace of visible structure.† The only possible conclusion to draw is that the development of the power of permanent magnetism in steel depends on the absence, and not on the presence, of visible structure. In looking for the origin of that power the microscope does not help us. The source is nowhere to be seen, and it must be sought by other means. It must be looked for among the molecules of iron, the molecules of carbon and other elements that enter into the composition of magnet steel.

Perhaps it is not only in the realm of permanent magnetism that the microscope fails to see the things that matter. In the past, micrographic study has greatly advanced metallurgical knowledge of the gross crystalline structure of metals and alloys, but to anyone who, like the present writer, is a mere intruder in the metallurgical field and therefore takes an outside view, it does not appear that the microscope, as a guide to the fundamentals of metallurgy, is likely to add appreciably to what it has already accomplished. Future progress seems to demand that optical vision should be replaced by mental vision, aided by some keener weapon than the microscope. Magnetism is such a weapon, but its application is limited at present to the magnetic elements. Another keen instrument of research, and one of more general application, is the X-ray spectrograph, which is already being widely used and bids fair to unravel many an obscure problem. Applied to metals, X-rays penetrate the molecular structure and reveal the arrangement of the atoms in the elementary crystal which forms the unit from which the gross structure seen in the microscope is built up.

It may be anticipated that before long the hypothetical molecular pattern, which Ewing's theory requires for the magnetic mechanism in iron and steel, will be put to the searching test of comparison with the pattern disclosed by X-rays. Whether the facts so revealed will fit in with an old and well-tried magnetic theory or whether that theory, like others before it, will have to give place to one in better agreement with newly discovered facts, no one can tell. But whatever the outcome of X-ray research may be, the discovery of the actual molecular pattern of the magnetic mechanism will be a forward step in magnetism second only in importance to the discovery of the planetary electrons.

Metallurgical knowledge and the facts of magnetism having been kept in reason-tight compartments (a metaphor we owe to Cuninghame Graham), the light to guide us in looking for the source of the magnetic power of the permanent magnet has mostly come from the magnetic phenomena themselves, phenomena which are now known to arise directly from the internal mechanism of the atom, the motion of the planetary electrons in their orbits constituting an electric current and endowing the atom or molecule with a powerful magnetomotive force. In the former paper an examination of the magnetic action of an assemblage of magnetic molecules enabled some sort of mental picture to be formed of the pattern in which the molecules would require to be arranged in order to give the whole mass the power of behaving like a permanent magnet. Now, steel containing carbon possesses that power in an eminent degree, and since the steel is known to be a solution of carbide molecules in iron, the inference must surely be that, in some way or other, the molecular pattern of solution constitutes the magnetic mechanism of the permanent magnet. It is easy to show by experiment with steels containing carbon, that the greater the development of the state of solution the more powerful the steel becomes as a permanent magnet. In this paper, therefore, the magnetic mechanism of Ewing's theory will be identified with the molecular pattern which is formed when carbon, in the form of carbide molecules of some kind, is dissolved in magnetic iron.

When embarking on the study of unfamiliar facts it never comes amiss to begin by acquiring a sense of the proportion of things, so that we may know beforehand whether we are to look for a mountain range or a speck of dust. The reader need not trouble about the mountain, for all the essential properties of the permanent magnet are to be found in a tiny fragment of steel, a mere invisible speck.

Turning to the microscope for the last time, what is the size of the smallest entity visible therein? How many molecules will it contain? To answer these questions the author has again availed himself of friendly help. When using a microscope with the high magnifying power of 3 000, Mr. Law found that the smallest entity which he could recognize with certainty as a metallic crystal grain, measured 105×10^{-6} cm

* E. A. Watson: "Permanent magnets and the relation of their properties to the constitution of magnet steels," *Journal I.E.E.*, 1923, vol. 61, p. 641.

† These statements are founded on an examination of microphotographs of tungsten magnet steel in different states of hardness. The samples were supplied by the author's firm in the form of cylindrical bar magnets and Mr. E. F. Law very kindly undertook the photographic work, for the purpose of this paper. The surface photographed was a transverse section near the middle of the length of each magnet. A magnifying power of 1 000 was used in taking the microphotographs.

in diameter. Assuming this tiny object to be a cube, it would contain $105^3 \times 10^{-18} \times 4 \cdot 2 \times 10^{22}$ molecules; in round numbers 50 000 million molecules. In the hardened steel of a permanent magnet a crystal grain, visible or invisible, is a homogeneous solution of carbide molecules in iron, and when considering a mass of steel as a solution the unit is the crystal grain. If the grain is large enough to contain 50 000 million molecules, we may just catch a glimpse of it in a powerful microscope as a minute structureless object of recognizable shape. More than that cannot be seen. The molecular pattern of solution is there in the tiny speck, the pattern which, in the view of the present writer, links metallurgical properties with permanent magnetism, but being a pattern of molecules it is, of course, far beyond the range of visibility in even the most powerful microscope. In short, apart from mental vision, nothing short of X-rays or magnetic phenomena can bring the molecular pattern of solution within our reach.

The iron-carbon solution, which constitutes the crystal grain in magnet steel, embodies also the magnetic machinery of the permanent magnet. But whereas the crystal grain may contain millions of molecules, a very small number will serve as a unit of magnetic action. With the aid of his celebrated working model of the magnetic mechanism, Ewing has shown that, so far as the magnetic phenomena of iron and steel are concerned, the whole secret of the magnetic machinery is contained in a group of a few dozen magnetic molecules. Looking on such a group as in some sense a unit portion of the magnetic machine, the crystal grain in its magnetic aspect is seen to be an assemblage of such units and quite likely to contain an immense number of them.

In the following pages, therefore, steel will present itself in two aspects, and when considering it as a solution the crystal grain must be borne in mind as the homogeneous unit. On the other hand, when looking at steel in its magnetic aspect, our attention will be directed to a tiny bunch of magnetic molecules, and not to the vast crowd of molecules which even the smallest visible crystal grain contains. But whether solution or magnetism happens to be foremost at the moment, our mental vision must be extended far beyond the gross appearances seen in the microscope, into a region where atoms and molecules are at work close to the very heart of things.

(2) The Theory of Magnetism in Iron.

Before considering the metallurgy of magnet steel, attention must be directed to one or two purely magnetic matters. The previous paper was founded on the combined theory built up by Ampère, Weber and Ewing, and in Part I it was shown that the power of a permanent magnet to maintain a magnetic field and resist demagnetizing forces depends on the ability of small groups of magnetic molecules to hold themselves together as local oriented systems, by means of their mutual induction. But in a mass composed of magnetic molecules of equal magnetomotive force, and uniformly distributed in space, local bonds of mutual induction, flux tubes threading small groups of molecules and binding them together by magnetic forces, are impossible, for lack of the necessary available spaces to contain them. Hence to set up the condition that gives rise to permanent magnetism there must be some kind of variformity in the distribution of magnetomotive forces, and since there is no reason to believe that the molecules of any magnetic element are unequal as regards their magnetomotive force, it follows that the required variformity must be a want of uniformity in the distribution of the magnetic molecules in space. It is more than likely that the want of uniformity is systematic; small groups of molecules being gathered together so as to leave vacant spaces available for the propagation of the mutual induction which, after magnetization, will serve as the magnetic bond between them. In the case of iron, which crystallizes in cubic order, it is natural to identify the gathered group with the eight molecules at the corners of a cube or primitive crystal; but this is rather a convenient mental picture than a hypothesis supported by facts. Evidently the variformity is a characteristic of the particular magnetic material, in a sense it is the structure of the material, and the greater the degree of variformity in any material used for making a permanent magnet, the greater the maintaining power of the magnet.

So much as a summary of the view of Ewing's theory put forward in the previous paper,* the basis being a molecule which is magnetic in virtue of the motion of its planetary electrons (Ampère's molecular current), and Weber's theory of magnetization as the orientation of a mass of magnetic molecules. Since the publication of that paper, Sir Alfred Ewing has suggested a modification of his original theory, his later view being that it is the planetary electron orbits only, and not molecules as a whole, that become oriented under the action of a magnetizing field; and that the power to retain the oriented state arises from the mutual induction between the several electron orbits of the individual atom or molecule. The fundamental principle of the original theory remains, but the origin of the retaining power has been transferred from the mutual induction of neighbouring molecules in a group, to the mutual induction of neighbouring electron orbits in an atom or molecule.† In this modified form the theory has not yet been developed to the point where it can replace the original theory as a guide in threading our way through the mazes of permanent magnetism, and in the present paper, as in the previous one, Ewing's theory in its original form will be assumed as a basis.

(3) Molecules: Magnetic and Non-Magnetic.

It is a strange fact that of all the known elements only three are magnetic at ordinary temperatures and under normal conditions. The magnetic elements are, of course, iron, nickel and cobalt, and in olden days when no one troubled about the inside of an atom these were the uncanny exceptions to the rule of no magnetism. But since it became known that every kind of atom contains electrons moving in orbits,

* "Permanent Magnets in theory and practice," Part I, *Journal I.E.E.*, 1920, vol. 58, p. 780.

† J. A. Ewing: *Proceedings of the Royal Society* A, 1922, vol. 100, p. 449; *Proceedings of the Royal Society of Edinburgh*, 1921–22, vol. 42, Part I, p. 97. *Philosophical Magazine*, 1922, vol. 43, p. 493.

and is therefore a potential source of magnetism, the difficulty has been to explain the absence of magnetic effects in the so-called non-magnetic elements. Iron, nickel and cobalt, with their powerful magnetism, are natural enough.

Weber saw the magnetic molecule as a little magnet. Ampère thought of its magnetism as arising from an electric current flowing in the molecule. It is now known that Ampère was right, the motion of the planetary electrons constituting the current. In the previous paper, when considering magnetization as an orientation of magnetic molecules, it was unnecessary to pay attention to individual electron orbits and, in order to provide a simple mental picture of the process of orientation, the several orbits of the molecule were all supposed to be lumped together, as it were, and regarded as equivalent in their effect to a single imaginary current ring behaving like a little coil carrying a permanent current.

We are, however, now going to look at the molecule of iron in its metallurgical aspect and, among other things, it will be necessary to take account of it as it exists when iron, being red-hot, ceases to be magnetic. We are therefore faced by the fact that iron can exist either in the magnetic or in the non-magnetic state, and the convenient image of the iron molecule as a single imaginary current ring behaving like a coil no longer serves. We must picture the iron molecule as equivalent to two equal current rings in order to have a system capable of changing from one magnetic state to another.

Iron loses its magnetism, apparently because each molecule loses its magnetic moment. What actually happens to the molecule is not known, but it is something equivalent in effect to a re-arrangement of the relative positions of the orbits of the planetary electrons. When the molecule is magnetic all the electrons belonging to it travel the same way round their orbits and endow the molecule with its magnetic moment and magnetomotive force. When the molecule is non-magnetic, the electrons must be travelling opposite ways in the different orbits, the numbers going one way and the other being such that the algebraic sum of the magnetic moments of the several orbits is zero. Hence the change from magnetic to non-magnetic, or vice versa, consists in a shifting of orbits from one arrangement to the other, a change that amounts to a reconstruction of the molecule.

For mental convenience we may suppose that there are only two orbits in the molecule of iron, each containing half the total number of planetary electrons belonging to the molecule. In this way we form a simple mental picture of the magnetic mechanism of the iron molecule as consisting of two imaginary current rings of equal and constant magnetic moment. If the currents in the rings go the same way so that their magnetomotive forces act in the same direction, then the system represents an iron molecule in the magnetic state. If the currents go opposite ways, then there will be no magnetic moment and no resultant magnetomotive force, and in that state the system represents the iron molecule in the non-magnetic state. To convert the system from one state to the other it is only necessary to turn one of the rings round, about a diameter, through half a revolution; and it is something equivalent in effect that takes place in the real iron molecule when the magnetic change occurs.

The energy required to convert a magnetic molecule into the non-magnetic state and the time occupied in effecting the magnetic change should be borne in mind when considering the metallurgical phenomena of iron and steel. To move two neighbouring coils relatively to each other, from positions in which their magnetomotive forces act in the same direction to positions in which they are opposed, requires the expenditure of force; energy must be supplied to effect the movement. If the coils are allowed to return to their original positions this energy will be released again. The same holds good for the simple model molecule composed of two current rings. Hence, assuming electron orbits behave like current rings and coils, any shifting of the orbits in an atom which has the effect of converting it from the magnetic to the non-magnetic state, will need a supply of energy to bring it about. This deduction from the known laws of electromagnetism is borne out by the facts, for there is a measurable absorption of energy when iron changes from the magnetic to the non-magnetic state, and the energy is released again when the iron returns to the magnetic condition.

Nothing is known from observation about the time occupied by an atom or molecule in effecting the magnetic change. However it is performed, it is an affair that concerns electrons and their orbits, and we may guess the time to be inconceivably short, more or less comparable perhaps with the periodic time of an electron travelling round its orbit. Now metallurgy has to do with various molecular transformations in iron and steel that progress quite slowly, occupying time measured by minutes or even hours, and sometimes, as we shall see in Section (16), stretching out into years. In comparison with even a single minute, the magnetic change of a molecule must be practically instantaneous, and it will be so regarded in the following pages.

(4) Coercive Force and Potency.

When magnets began to be made of steel it was soon recognized that besides the magnetism of the steel there was some other property, some hidden power, that went to the making of a permanent magnet. In iron this power was almost entirely absent. Steel, although less magnetic than iron, possessed far more power to act as a permanent magnet, and in hardened steel the power was present in the highest degree. To this mysterious property, latent in the steel before it was magnetized, the misleading name "Coercive Force" was given in very early days. Hard steel, for example, was said to possess a great coercive force; though what the steel was supposed to coerce it would be hard to say at this distance of time. However, there the property was, and coercive force it was called. To-day the property is still recognized as inherent in the steel, but the old name for it has long been transferred from the steel to a purely magnetic quantity

which happens to serve, in some degree, as a measure of the coercive force property.

This confusing transference of name was made some forty years ago by Hopkinson. Finding the term coercive force already in use, and perhaps hardly realizing the meaning it held for the maker of permanent magnets, he attached it to the demagnetizing force which serves to reduce the flux in iron or steel to zero. To speak in a parable, a certain man in authority transferred the name coal from the black lumps in a sack to the weights employed in weighing it; and to this day men call the weights "coal," much to their own mental confusion. Hopkinsonian coercive force is the weight. The property latent in the steel, the coercive force known to the magnet maker, is the coal.

At this time of day it would be futile to attempt to re-name the demagnetizing force that reduces the flux to zero. Coercive force it has been for all of us since Hopkinson's time, and coercive force it will doubtless remain. But it must not be forgotten that it is purely a magnetic quantity, one which affords a sort of measure of the ability of the magnetized mass to withstand the action of demagnetizing forces.

Knowing that iron possesses scarcely a trace of the power to withstand demagnetizing forces and that steel has it in a high degree; knowing, moreover, that steel differs from iron in composition, we are justified in believing that the withstanding power has its origin in some particular molecular arrangement, a molecular pattern, so to speak, highly developed in hard steel, almost non-existent in soft iron. Whether we are always clearly conscious of it or not, it is the power latent in the molecular pattern that we have in mind when we refer to the coercive force *of the steel.* To avoid confusion it is essential to realize that although we use magnetic means to detect it, the *coercive force of the steel* is not itself a magnetic property. It is there in the steel, as a molecular pattern, whether the steel is magnetized or not. It is the coal, and must not be confused with the Hopkinsonian weight.

In the following pages, in order to avoid circumlocutions when referring to the withstanding power latent in the molecular pattern, it will be called the "potency" of the steel, and Hopkinson's coercive force will be regarded as a convenient indicator of different degrees of potency in different kinds of steel.

According to the theory on which this paper is founded, potency must have its origin in some kind of systematic variformity in the distribution of the magnetic molecules, and hence in the light of that theory the molecular pattern is the variformity. But variformity implies the particular theory associated with the names Ampère, Weber and Ewing, and a word specifically adapted to a theory is always open to the objection that some day the theory may be replaced by a better one, and in that event the word becomes misleading. The terms molecular pattern and potency are free from this objection.

In a piece of pure iron the volume is occupied solely by magnetic molecules. Iron possesses hardly any potency and, to make it fit for a permanent magnet, potency must somehow be imported into it. So far as knowledge goes at present, this cannot be done on an adequate scale without introducing non-magnetic substances into the iron, and since the non-magnetic molecules replace some of the magnetic molecules, a piece of iron can only acquire potency at the sacrifice of some of the inherent magnetism. It is easy to make steel of great potency if the accompanying sacrifice of magnetic molecules is ignored, but the true art in making magnet steel consists in carefully balancing gain in potency against loss of magnetic molecules. This principle has often been overlooked by steelmakers.

In the following sections, the molecular pattern that gives rise to great potency will be identified with the arrangement of molecules in a solution. Knowledge of solutions is not yet sufficiently advanced to enable a clear mental picture of that arrangement to be formed, but, whatever may be the state of things in a solution, it certainly provides the kind of molecular pattern that gives potency.

(5) THE STATE OF SOLUTION.

The metallurgical aspect of steel as a solution has already been referred to. It is a strange kind of solution. Not so much because it happens to be in the solid state, as for other reasons that will unfold themselves as we go along.

For most of us a solution is a liquid with something dissolved in it, like salt in water. So familiar is the fact that salt dissolves in water, that no explanation seems called for until we begin to wonder what the molecules of salt are doing in the water. When we inquire of the learned what is the relationship between the salt and the water, the solute and the solvent, no very definite answer is forthcoming. Everything, or nearly everything, seems to be known about solution except what it is. It is easier to say what it is not. Solution is not a mere mixture in which the molecules of different kinds pay little or no attention to each other. On the other hand, solution is not chemical combination, for that is an affair of atoms and definite proportions, whereas the constituents of a solution can exist together in any proportions within limits.

When a solution is examined some little time after dissolving the solute substance in the solvent, it is found that the solute has become uniformly distributed throughout the liquid. To do this, the solute molecules must have been acted on by forces akin to those which cause the molecules of a gas, contained in a closed vessel, to distribute or disperse themselves uniformly. In the case of the gas the ultimate effect of the molecular dispersing forces is a pressure on the walls of the vessel and on the surface of any body inside the vessel. Similarly, in a solution, the solute molecules exert a pressure, and apparently gas pressure and solution pressure are of the same nature, if indeed they are not identical. In a solution the solvent seems to fulfil the function of the space inside the closed vessel, and just as the molecules of gas are confined within the vessel so the molecules of solute are confined within the volume of the solvent.

The mobility of solute molecules in a liquid or solid solution is naturally very much less than that of molecules in an otherwise empty space. A bunch of mole-

cules when put into an empty vessel would disperse with extreme rapidity and almost instantly become uniformly distributed. But a similar bunch of solute molecules in a liquid would find their movements hampered by the presence of surrounding molecules of solvent and, with diminished freedom to travel, the dispersal of the molecules would, of course, go on much more slowly. In a solid it must be even more difficult for molecules to travel from place to place. Nevertheless, when a solution is in the solid state, the solute molecules do manage to move about when the forces are there to set them in motion. But the greatly restricted molecular mobility in the solid naturally makes travelling exceedingly slow.

When the constituents of a solution have widely different properties, as in the case of salt and water, or when one constituent greatly exceeds the other in quantity, as in a dilute solution, it is useful to mark the difference by the words solute and solvent. But in metallic solutions, more generally known as alloys, it is impossible to distinguish between the constituents in that way and solution is then seen to be a mutual condition, each constituent being, as it were, dissolved in the other. But solutions of the completely mutual kind are very different from the one-sided solution with which we are concerned in this paper. When carbon, combined with some other element to form a solute molecule, is dissolved in iron, the two constituents play entirely different parts. Nothing can make the carbon do what the iron does, nor can anything make the iron act like carbon. For this reason it will be convenient to adhere to the terms solute and solvent, although nowadays these words have lost some of their distinctive meaning.

At any given temperature there is a limit to the quantity of solute which a given volume of solvent can hold in solution, and when the solution contains that limiting quantity it is described as a saturated solution. If the temperature of a saturated solution is lowered to some other point, a sufficient quantity of solute will pass out of solution to leave the solution in the saturated state which corresponds with the lower temperature. The surplus solute which comes out of solution in that way makes its appearance as a separate substance, and if the solute is naturally a crystalline substance the surplus will appear in the form of tiny crystals.

When a surplus quantity of solute passes out of solution and assumes the crystalline form, the solute molecules are required to travel from the positions they occupy as constituents of a solution to the positions they must take up as members of a crystal, a procedure somewhat analogous to what happens in a squad of soldiers on the order to form fours. Hence to pass from solution to crystal each solute molecule must make a journey; and journeys, however short, take time. The time taken on any particular molecular journey will depend on the propelling force acting on the molecule, and on the molecular mobility. In solid steel we must be prepared to find the solute constituents taking time measured by minutes or days, or even it may be years, to accomplish the passage from solution to crystal.

The solute molecules, the pressure of solution, the surplus solute, the molecular mobility, the journeys of the solute molecules on their way from solution to crystal, and the time occupied on the journey, are all matters intimately connected with steel as a solution, and for that reason attention has been drawn to them at the outset. It seemed all the more necessary to do so, because metallurgical textbooks, for the most part, bury the molecule and its doings under a tumulus composed of microphotographs, equilibrium diagrams, and the phase rule of Willard Gibbs.

(6) Steel as a Solution.

Every kind of steel is a solution, many of the elements, both alone and in combination, being soluble in iron. The solutes not only dissolve in molten iron, but remain in solution when the iron cools down and becomes solid. Moreover, certain elements will actually pass very slowly into solid iron and dissolve in it, taking many hours to do what is done in a few seconds in a liquid solvent. This brings us at once to the difference between a liquid solution and a solution which, like steel, is in the solid state. The difference is not fundamental. In the main principles underlying the behaviour of solutions, solid and liquid solutions are alike. It is in the element of time that they differ. In a solid the mobility is so small compared with that of a liquid like water, for example, that molecular journeys, such as those of the solute molecules on their passage from solution to crystal, occupy immensely longer times. On the lowering of the temperature of a liquid solution like salt water, the passage of the solute molecules from solution to crystal is so quick as to appear almost instantaneous; whereas in solid steel even when heated red-hot to give greater mobility, the same process is found to occupy several minutes, as we shall see in a later section. When the steel is cold (at room temperature) the mobility is so slight that in practice it is ignored and the cold steel is regarded as being in an unchangeable condition. Nevertheless, there is evidence that even when cold the mobility is not quite zero; the molecules can, and do, go on journeys, although with almost incredible slowness. Novel evidence of this will be given on a later page. On general grounds it seems probable that the mobility does not actually vanish until the temperature falls to the absolute zero.

Turning now to the solutes in steel, of the many elements that are commonly used at the present time we are only directly concerned with carbon, tungsten and chromium. Of these the first was accidentally introduced into iron in the Early Iron Age. The other two have been brought into use in more recent times as the result of efforts to increase the hardness of tool steel. Hardness and potency being both associated with the state of solution, steels which lent themselves by their hardness to the making of tools have sometimes proved to make good magnets.

It is an easy matter for the steelmaker to dissolve all manner of elementary substances in iron and describe the resulting product as steel. But to ascertain what happens to the various elements jumbled together in this way, whether they combine and if so

in what chemical forms, has been a task of the greatest difficulty, and it has needed much patient research by many metallurgical workers to determine the composition of the various solute molecules met with in steel. Naturally carbon was the first to be attacked. It has been conclusively demonstrated that under ordinary conditions carbon only dissolves indirectly in iron. It does so by combining with some suitable element to form a compound solute molecule. Iron itself happens to be one of the suitable elements, and when carbon is put into iron, each atom of carbon combines with three atoms of iron to form a molecule of carbide of iron, Fe_3C.* This substance being soluble in iron, the molecules so formed immediately dissolve in the remaining iron; and since iron is only capable of dissolving a small proportion of this or any other carbide, the remaining iron constitutes much the greater part of the whole mass. Another suitable auxiliary element is tungsten, which combines with carbon as a carbide of tungsten, WC, which is also soluble in iron. A third element of the auxiliary kind is chromium, which combines with carbon as a carbide of chromium having the formula Cr_3C_2.† Several other suitable elements of the auxiliary kind are employed in combination with carbon as solutes in different kinds of steel, but we may confine our attention to carbide of iron (Fe_3C), carbide of tungsten (WC), and carbide of chromium (Cr_3C_2), since apart from alien substances these three compounds alone are met with in magnet steels at the present time. In carbon steel, only the carbide of iron is present. In tungsten magnet steel, carbide of iron and carbide of tungsten are both used and in such proportions that there are roughly the same number of molecules of each. In chromium steel both the carbide of iron and the carbide of chromium are likely to be present, but as this steel is inferior to tungsten steel as a material for permanent magnets its composition has not received much attention.

Each of the three carbides just referred to is soluble in iron to a small extent; and when in solution, but not otherwise, each endows iron with potency. The greater the quantity of carbide in solution the greater the effect, up to a limit which is reached when the proportion of carbide compound, reckoned in terms of its carbon content, is about one per cent of the weight of steel. In treating of magnet steels, therefore, we are not concerned with any steel containing more than about one per cent of carbon.

There is no simple quantitative relation between the proportion of carbide in solution and the resulting potency of the steel; but by ascertaining the quantity of carbide by analysis and determining the potency by measuring the Hopkinsonian coercive force, a curve can be prepared connecting the carbon content with the coercive force and therefore establishing the relation between the particular solute molecule and the potency it creates in the iron. Curves of this kind have been experimentally determined by Madame Curie for carbon steel, and by the present writer for tungsten steel. These curves will be found in the sections of the present paper devoted to carbon steel and tungsten magnet steel, the author's curve, giving the carbon content and coercive force of tungsten steel, being now published for the first time.

The three carbides used for magnet steels differ in their power of creating potency. As a unit, a molecule of tungsten carbide is considerably more effective than one of iron carbide; nevertheless, the maximum value of the potency of a steel which contains only the carbide of tungsten is no greater than that of carbon steel. When both these carbides are present, as they are in tungsten magnet steel, they yield a far higher potency acting together than either carbide does by itself. This amplifying power might possibly be explained by supposing the two carbides to unite to form the double carbide Fe_3CWC, provided that molecule could be shown to possess a greater potency-giving power. But the evidence of analysis, and some newly acquired magnetic evidence referred to later on, seem to point quite clearly to the presence of the two carbides as separate entities. Which is the true view no one can say for certain, and how these two carbides by working in conjunction as solute molecules in tungsten magnet steel manage to create a greater potency than either solute can do by itself is a problem for the future to unravel.

The most powerful solute considered solely as a source of potency is the carbide of chromium, the molecule of which is some eight or nine times as powerful as a molecule of carbide of iron. Unfortunately, carbide of chromium also has the power of preventing molecules of iron from assuming the magnetic state. Although as a solute molecule it provides great potency, yet at the same time carbide of chromium greatly depletes the steel of its magnetic molecules, and the loss of magnetic power from this cause outweighs the gain in potency. For this reason chromium steel is inferior to tungsten steel as a material for permanent magnets. But by the introduction of another solvent, namely an alloy of cobalt with iron, Professor Honda appears to have removed this drawback and for the first time enabled carbide of chromium to be used without robbing magnetic molecules of their magnetism.

Potency and hardness go together in steel, both properties depending mainly on the presence of carbide molecules in solution. The same carbides, not in solution but present in the steel as distinctive crystalline substances, yield no potency. Presumably they give no hardness either.

None of the elements forming the three carbides used in magnet steels seem able by themselves to create potency. This is certainly true of the iron in carbide of iron. It also applies to tungsten. This element, when put into iron, combines with it to form the molecule Fe_2W,* which, being soluble, immediately dissolves in the remaining iron. But experiment shows that the presence of this solute gives the iron no potency. From analogy it may be conjectured that

* Fe_3C expresses the true proportion, and that is all that is material to the argument of the present paper. Whether the actual molecule is Fe_3C or Fe_6C_2 or $2(Fe_3C)$ does not seem to be known.

† ARNOLD and READ: *Journal of the Iron and Steel Institute*, 1911, vol. 83, p. 249.

* ARNOLD and READ: *Proceedings of the Institution of Mechanical Engineers*, 1914, pt. 2, p. 223.

chromium by itself is ineffective as a creator of potency, but there is no experimental evidence on the point. Lastly, carbon, by itself, is not able to endow iron with potency. Under some conditions carbon in its elementary form, not in combination with other elements, "free carbon" as it is called, is found in steel; even in steel which contains less than one per cent of carbon. Whether it is in a state of solution or not does not appear, but whatever the atoms of free carbon may be doing they are certainly not creating potency. Experimental evidence for this statement has long been available, and on a later page novel evidence will be given that free carbon does not endow iron with potency.

Although this brief examination of the action of each element of the various carbides has failed to identify the potency-creating power with any particular element, there is one consideration that seems to provide a clue. Each of the three carbides used in magnet steels is an effective creator of potency, and when it is borne in mind that the only thing these carbides possess in common is carbon, it is difficult to resist the conclusion that in a solute molecule that creates potency, carbon is the dominant element. True, it does not act by itself. Alone it is powerless, and apparently it is necessary for it to combine with auxiliary elements; yet when so combined in a solute molecule the atom of carbon appears to play the leading part.

If iron were an ordinary element, the rest of the story of steel as a solution could be told without more ado. It would almost suffice to refer to some good textbook treating of solutions in general,* for apart from the extreme slowness of travelling molecules in a solid, steel would behave much in the same way as the more familiar liquid solutions. But if there is any such thing as an ordinary element it is certainly not iron. It would be less wide of the mark to describe solid iron as four interchangeable elements, for it can exist in any one of four states which differ from one another almost as widely as one element differs from another. Of these four different kinds of matter, all described as iron, one is familiar to everyone because it happens to exist at ordinary temperatures. Of the other three it can only be said, at present, that although beyond the reach of the chemist, they are gradually becoming known to the metallurgist. It is this anomalous kind of matter that plays the part of solvent in steel, and its protean transformations must now receive attention.

(7) Iron as an Allotropic Element.

The word "allotropy" was coined a hundred years ago by the chemist Berzelius to describe certain strange substances, visibly and quite remarkably different in outward form, yet chemically indistinguishable from one another, and therefore presumably merely different forms of the same element. Carbon,† which takes the form of diamond, or graphite, or soot, is a familiar example. Another example is sulphur, which can exist as beautiful yellow crystals or as a sticky brown mess. Iron is not allotropic in this obvious sense; it undergoes no visible or tangible changes. Yet its allotropic transformations, although they make no direct appeal to our senses, are even more extraordinary than the difference between diamond and soot.

The recognition of iron as an allotropic element has been a long time coming. The first sign appeared so long ago as the year 1600 when Gilbert, the early father of permanent magnetism, discovered that iron, when heated red-hot, became non-magnetic. Then, to come at once to more modern times, some fifty years ago Gore discovered a whole series of changes taking place in red-hot iron. He found that in addition to the magnetic change, the specific heat, electric conductance, molecular structure and other characteristics, all showed marked changes when iron is heated above a red heat, indicating that it was far from being a normal element. Somewhat later Barrett discovered the phenomenon of recalescence, another sign of allotropy.

But the first systematic investigation of the allotropy of iron was begun in 1887 by F. Osmond, who set out to determine the temperatures at which iron changes from one state or variety to another. Every transformation of the kind is accompanied by an absorption or emission of energy in the form of heat, and on a time-temperature curve obtained from a test specimen that is being gradually heated or cooled an absorption or release of energy will be indicated by a more or less sudden, but temporary, alteration in the slope of the curve. It is possible to ascertain the temperature at which an allotropic transformation takes place by noting the position of the corresponding change in slope, but usually the changes in the slope of time-temperature curves are slight and by no means easy to detect with certainty. Osmond got over this difficulty by making direct observations of the slope itself. In principle, the quantity to be observed is the rate of change of temperature with time, or the reciprocal of that quantity. In practice it is easier to observe the reciprocal or inverse rate, and Osmond's inverse rate curve is obtained by observing the successive intervals of time corresponding with successive small increments, or decrements, of temperature, the time intervals being plotted as co-ordinates with the temperature. Any departure from the normal rate of heating or cooling is indicated by a marked excursion of the curve from its normal course, and hence excursions indicate absorption or release of energy by the specimen under test. By this ingenious method of observation Osmond definitely ascertained the existence of three allotropic varieties of iron, and provisionally determined the temperatures which constitute the boundaries between the different varieties.

The information afforded by Osmond's inverse rate method, and other differential methods derived from it, is mainly qualitative. An excursion of the curve from the normal course indicates the fact that an absorption or emission of energy took place, and points to the temperature at which the phenomenon began, attained its greatest activity, and came to an end. But that is all. Moreover, the time element only

* Mr. Whetham's "Theory of Solution" (Cambridge University Press) gives a comprehensive account of the subject.

† Carbon again! But this time merely as a handy illustration and not as the dominant element in a solute molecule.

appears as a differential, and to ascertain the duration of any absorption or emission of energy it is necessary to integrate the inverse-rate curve. The author has naturally made constant use of Osmond's method, but in this paper it will be necessary to pay particular attention to duration, because time is the key to hardening, and for that reason the allotropic changes in carbon steel and tungsten steel will be illustrated by curves plotted to a scale of time.

To acquire a sense of proportion with regard to the various allotropic transformations, it is necessary to measure the energy changes associated with them. This has frequently been attempted, usually with inconclusive, if not erroneous, results. The first experiment of the kind was made by Hopkinson, who tried to measure the energy released in iron and in carbon steel during the magnetic change.* Up to the present time the best experimental values are those obtained incidentally by Wüst, Meuthen and Durrer in the course of their recent determinations of the specific heat of pure iron in its different allotropic states.† Their method was to heat the test specimen to the required temperature and then to drop it into a Bunsen ice calorimeter and measure the total energy, each experiment being performed from beginning to end in a vacuum. In this way specific heats were determined with remarkable accuracy. The allotropic energy of the different transformations is readily deduced from the observational data, and the temperatures at which the transformations occurred were ascertained with a precision not previously attained. Pure electrolytic iron was employed, hydrogen and any other gases present in the iron being removed by melting the test specimen under a vacuum.

The more important facts relating to the allotropy of pure iron are given in Fig. 1 in the form of a diagram, in which the boundaries between the different varieties are shown against the scale of temperature. The diagram has been prepared by the author to represent present-day knowledge so far as possible, and is of course founded on the researches of Osmond and those who have followed him, with the addition of the quantitative data determined by Wüst and his co-workers. In the case of the energy which is absorbed or emitted over a somewhat ill-defined range of temperature extending from about 800° C. downwards, nearly to 0° C., the major portion arises from some unknown cause, and occurs below the point at which iron loses or regains its magnetism. It seemed worth while to distinguish between this unidentified energy and that properly attributable to the magnetic change, and the present writer has therefore computed the two quantities separately from the observational data given by Wüst. The values so calculated have been inserted in Fig. 1.

Osmond, having recognized the existence of three allotropic varieties of iron, named them "Alpha iron," "Beta iron" and "Gamma iron," in the order of ascending temperature. More recently a fourth variety has been discovered between Gamma iron and molten iron, and this is referred to as "Delta iron." Whether at temperatures below 0° C. iron assumes any other allotropic states does not seem to be known.

Ordinary iron, the most familiar of all metals, is Alpha iron. It is the iron of chemistry and has an international atomic weight of 55·85.* The specific heat at 0° C. is 0·1055, precisely what theory expects

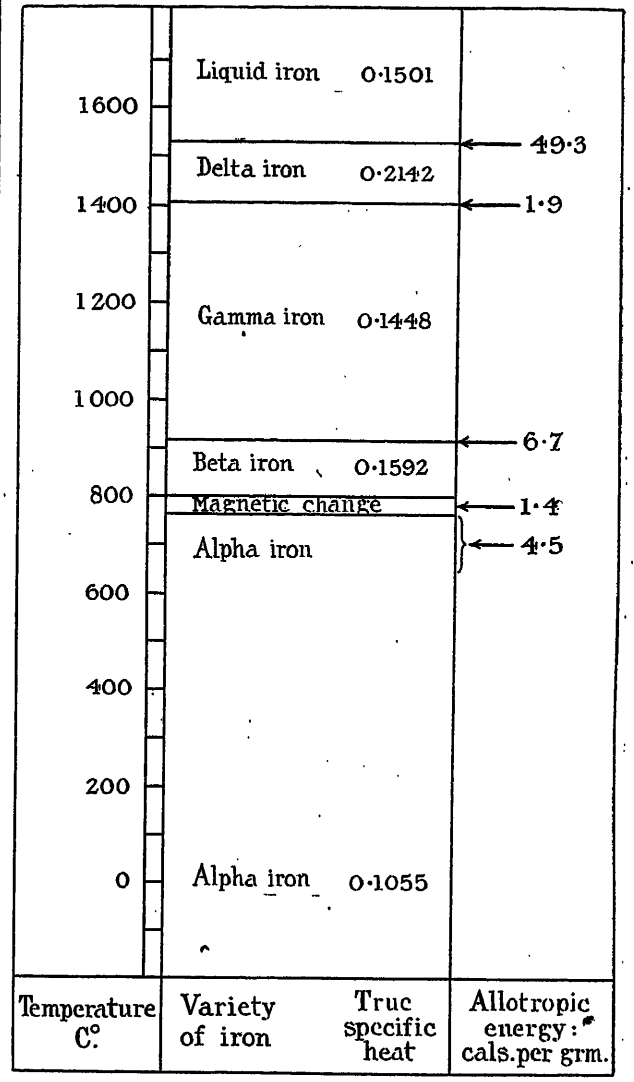

FIG. 1.—Allotropic varieties of iron.

it to be.† In short, Alpha iron behaves in every way as an old-fashioned chemical element should do.

Alpha iron is magnetic, the molecule of two atoms having a magnetic moment of about $4 \cdot 0/10^{20}$ C.G.S. units. With this moment, when all the Alpha molecules in a given volume are fully oriented, the magnetic moment of the oriented or magnetized mass is 1 700

* JOHN HOPKINSON: "Magnetic and physical properties of iron at high temperatures," *Proceedings of the Royal Society*, A, 1889, p. 464.

† WÜST, MEUTHEN und DURRER: "Die Temperatur-Wärmeinhaltskurven der technischen wichtigen metalle" *Forschungsarbeiten auf dem gebeite des Ingenieurwesens*, 1918 No. 204.

* It would appear that there is some International Body which looks after the elements and their atomic weights.

† On the kinetic theory of gases the formula for specific heat is $\frac{1}{2}(n + 3)R/Jm$, where R is the gas constant, J the number of ergs in one calorie, m the mass of the atom. In a solid n is 3, and on this basis the specific heat of solid iron should be 0·1053, which agrees well with Wüst's observed value, 0·1055 at 0° C.

C.G.S. units per cm³; equivalent to a permanent magnetizing force of 17 000 ampere-turns per cm of length along the axis of magnetization.

For the purpose of this paper it is unnecessary to describe in detail the many phenomena observed in iron as the temperature is raised from 0° C., or thereabouts, to the melting point. But attention may be directed to the more significant among them, in order to mark the fundamental character of the allotropic modifications.

The first indication of anything abnormal in the behaviour of iron, as it is heated, is the gradual increase in the apparent specific heat,* a sure sign that the heat communicated to Alpha iron is not all utilized in raising the temperature; some of the energy taken in as heat is doing something else, probably effecting a change of some kind in the structure of the iron. This *precursor effect*, to give it a name, is noticed in nearly all metals, and it generally occurs as the melting point is approached. The singularity in iron is that the precursor effect seems to have no relation to the melting point. It becomes noticeable immediately above 0° C. and comes to an end somewhere about 750° C., a temperature nearly 800 degrees below the melting point. It seems that in iron the usual precursor effect occurs once for all while the iron is in the Alpha state, for it is significant that there is no such effect just below the melting point. It is a curious fact, and possibly one of significance, that the extraordinary temperature variations in the magnetization of Alpha iron, discovered by Hopkinson,† closely follow the course of the precursor effect. We are, however, not directly concerned with the precursor effect and it must be passed over with this bare reference.

At about 770° C. Alpha iron begins to change into Beta iron. This transformation is effected within a temperature range of about 40 degrees and is practically complete at 810° C.* Alpha iron is magnetic, Beta iron is entirely non-magnetic. That is to say, when iron passes from one state to the other the molecules, one after another, transform their electron orbits from the magnetic arrangement, in which their magnetic axes all point the same way and endow the Alpha molecule with its known magnetic moment and magnetomotive force, to the non-magnetic arrangement in which the algebraic sum of the magnetic moments of the orbits in the molecule is zero. In plain English, when Alpha transforms itself into Beta, iron becomes virtually a different element, the molecule having been reconstructed on a different plan. This fundamental reconstruction is marked not only by the entire loss of magnetic moment and magnetomotive force, but by an equally significant change in the specific heat; a change which points directly to some kind of atomic reconstruction.

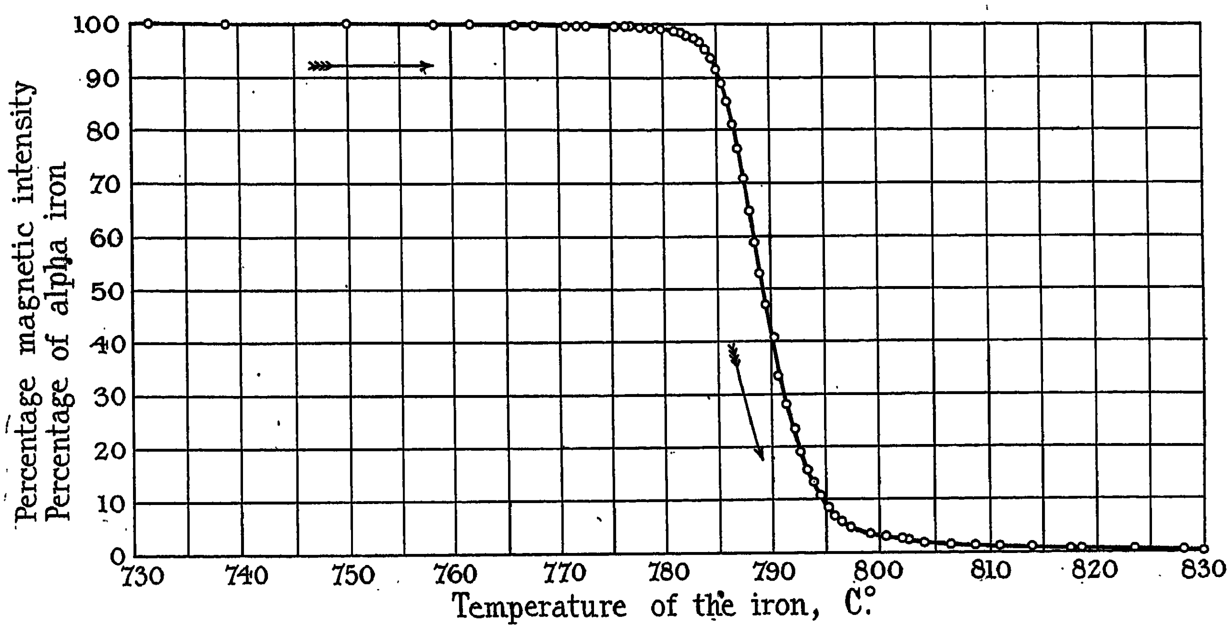

FIG. 2.—Loss of magnetism in pure Swedish iron.

Alpha iron being magnetic and Beta iron non-magnetic, the curve exhibiting loss of magnetism as the temperature rises from 770° to 810° C. indicates with the greatest precision the progress of the allotropic change from Alpha iron to Beta iron.† A curve of this kind determined for the purpose of this paper, from a specimen of very pure Swedish iron, is shown in Fig. 2. The intensity of magnetization is expressed

* When considering allotropic changes, specific heat is a trap for the unwary. Definitions of specific heat tacitly assume that the whole of the heat communicated to the substance goes to raise its temperature. When that is so then the quantity measured is the *true* specific heat. But when an allotropic change is in progress and absorbing energy, some of the heat supplied to the substance is used for that purpose and only the balance goes to raise the temperature. The observed quantity is then the *apparent* specific heat. The apparent specific heat of boiling water or a melting metal, or of iron changing from Gamma to Delta, is infinite.

† J. HOPKINSON, loc. cit.

* Very slight differences in the condition of pure iron, the presence of traces of absorbed gas, and other causes, are found to affect the temperatures at which the allotropic changes occur, frequently by as much as 10 degrees and sometimes even more. For this reason all the temperatures given in the text must be regarded as liable to modification. They are in all cases values actually observed in particular experiments.

† The author is responsible for this truism. No such statement is to be found in the textbooks. Indeed, whenever magnetism comes into view metallurgical writers seem only too ready to pass it by on the other side.

as a percentage of the intensity observed when the iron was wholly of the Alpha variety, and consequently the percentage intensity at any stage in the transformation is also the percentage of Alpha iron in the total mass of iron. Towards the end of the transformation the magnetic intensity approaches zero so very gradually that it is impossible to give an exact figure for the width of the temperature zone within which the entire change from Alpha to Beta is effected. But examination of a number of curves of the loss and recovery of magnetism in pure iron shows that 99 per cent of the whole transformation is effected within a temperature range of 37 ± 1 degrees, so that the width of the temperature zone of the magnetic change from Alpha to Beta, or vice versa, may be put in round figures at 40 degrees for pure iron. The re-arranging of the electron orbits in any individual molecule

put at 919° C., Beta iron is entirely converted into Gamma iron, provided sufficient time is given to effect the change, which is essentially a slow process. On passing the boundary formed by the critical temperature the mechanical and other properties of iron undergo further abrupt changes; but there is no magnetic change, Gamma iron being non-magnetic. The specific heat of Gamma iron is constant.

At a critical temperature, which Wüst has determined as between 1 404° and 1 405° C., Gamma iron is transformed into Delta iron, with a sudden increase of 50 per cent in the specific heat. The iron remains in this state up to the melting point and, the specific heat of Delta iron being constant, there is clearly no absorption of energy as a precursor to fusion.

Last of all, at 1 528° C. pure iron melts. There is a large absorption of energy, a sudden decrease in

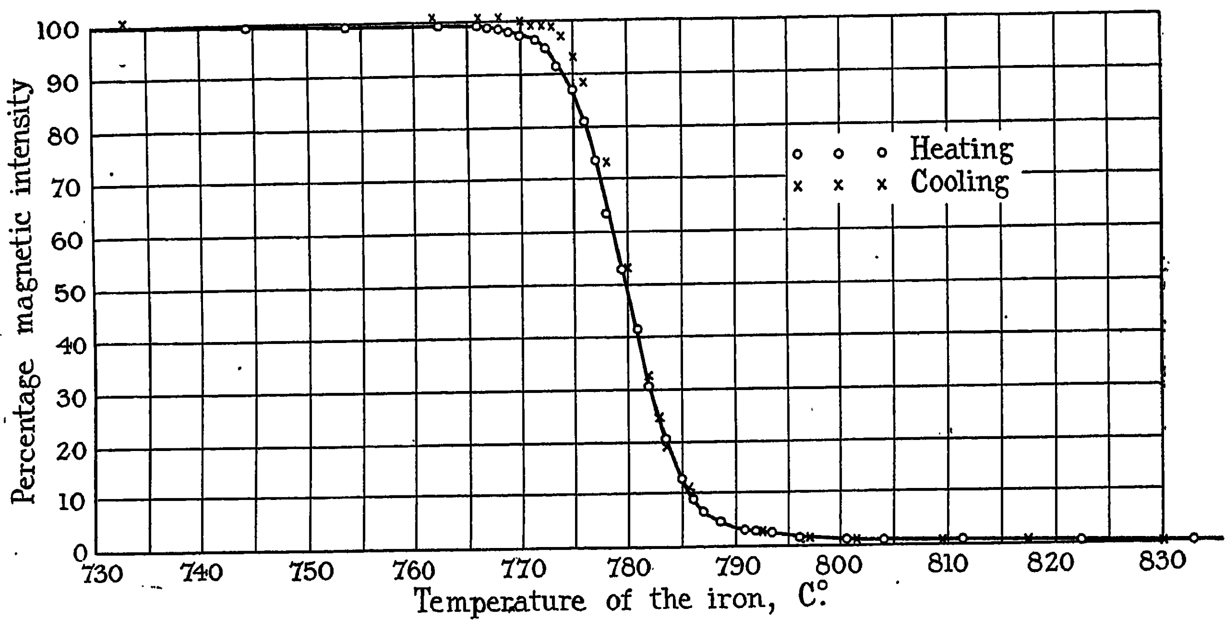

Fig. 3.—Curves of loss and recovery of magnetism in pure Swedish iron.

of iron being practically instantaneous, the width of the temperature zone should be entirely unaffected by differences in rates of heating and cooling. The author has verified this for rates varying from 1 degree a minute up to 12 degrees a minute, there being no observable difference in the width of zone within these limits.

At any given temperature within the narrow zone of 40 degrees, Alpha and Beta molecules exist together, in equilibrium, in a definite proportion, like two metals in an alloy. Any change in temperature in either direction is necessarily accompanied by a corresponding change in the proportion of Alpha molecules to Beta molecules. Besides the magnetic change, abrupt changes in mechanical and other properties are noticed as Alpha iron changes into Beta iron. The specific heat of Beta iron is constant, indicating that all heat communicated to it goes to raise the temperature.

The next transformation occurs at a critical temperature which Wüst found to be somewhere between 918° and 920° C. At this temperature, which may be

specific heat, a remarkable change of state, and an abrupt and total loss of mechanical strength. All these are characteristic symptoms of an allotropic change, yet for some reason, or for no reason, fusion is not included among the allotropic changes.*

When molten iron cools, the allotropic transformations take place in the reverse direction, one after the other, and the allotropic energy absorbed at each change of state is released again and appears in the form of heat. Many observers have noticed that, on cooling, the transformations occur at temperatures a few degrees below the points at which they took place when the temperature was rising, but careful observation has failed to disclose any difference in pure iron between the temperature of the change from Alpha to Beta and the reverse change from Beta to Alpha. This is illustrated in Fig. 3, which records an experiment on the point made for the purpose of this paper.

* The probable reason is that fusion was discovered by primitive man; and being primitive, he knew nothing of the art of coining a word from the Greek whenever anything happens that is not understood.

The curves of loss and recovery of magnetism given in the figure show that within the limits of experimental error (about 2 degrees C.) the change from Alpha to Beta coincides exactly with that from Beta to Alpha. The author has obtained similar curves at widely different rates of heating and cooling without finding any evidence, so far as pure iron is concerned, that the position of the temperature zone of this transformation on the scale of temperature shifts up or down according to whether the iron is being heated or cooled.

Among the allotropic phenomena briefly described in the preceding paragraphs, two are of primary importance, namely, the magnetic change and the marked changes in specific heat. Both point directly to some change in the atom or molecule. The kind of reconstruction implied by the magnetic change has already been indicated. The import of a sudden change in specific heat is equally fundamental. True specific heat is inversely proportional to atomic weight, and the specific heats of the four varieties of iron, namely 0·1055, 0·1592, 0·1448 and 0·2142, correspond with atomic weights of about 56, 37, 41 and 27. Hence if it were not known that Alpha, Beta, Gamma and Delta were varieties of iron it might well be supposed that they were four distinct elements of those atomic weights. Now 56, 37, 41 and 27 being approximately the atomic weights of iron, chlorine, calcium and aluminium, the natural inference to draw seems to be that Alpha, Beta, Gamma and Delta iron differ from each other in much the same degree as those four elements do. It is not suggested that iron which begins as an irreproachable international element actually converts itself successively into chlorine, calcium and aluminium, but it manifestly does something quite as revolutionary in effect.

So far no explanation of the allotropy of iron has been forthcoming. The specific heat of Delta iron being about twice that of Alpha, it might be supposed that the atom of Alpha iron breaks up to form two atoms of Delta, the positive nucleus of the Delta atom containing half the number of protons and therefore constituting an atom of about half the atomic weight. But conjecture, however plausible, is of little use, and the time is hardly ripe for an explanation of the allotropy of iron. It will eventually come from a better knowledge of the construction of the atom and the way it works as a dynamic system.

(8) Carbon Steel.

Turning again to the consideration of steel as a solution, we come back to our subject fully aware of the extraordinary nature of the solvent iron. It is in this shifty element that the several kinds of carbide used in magnet steels must be dissolved. Now the carbides dissolve freely enough in Delta, Gamma and Beta iron, but these varieties of iron all being non-magnetic are, of course, useless as the foundation of a permanent magnet. To make a magnet the steel must be magnetic, that is to say, the iron must be in the Alpha state, and unfortunately none of the carbides at present available for use in magnet steel dissolve in Alpha iron, under normal conditions, in sufficient quantity to make a powerful magnet. In these circumstances, in order to convert the steel into a material fit for the purpose, it is necessary to make use of a process of unique character handed down to us from time immemorial. The steel is first heated so as to transform the iron into Beta or Gamma, in order that a sufficient quantity of carbide may be dissolved in it, and then, by means of the ancient process called hardening, the whole quantity can be retained in solution when the iron, on cooling down, returns to the Alpha state. The state of things brought about in this way is quite abnormal, the solution being in unstable equilibrium; nevertheless, no better way of making a good permanent magnet is known at the present time.* A comprehensive account of hardening will be found in Section (15), and in the meantime it is enough to know that in hardened magnet steel all the solute carbon compounds are held in solution, thus giving the steel the required potency.

Nowadays, carbon steel is seldom or never used for permanent magnets; but as a solution containing only one solute substance, the carbide of iron Fe_3C, it will afford the simplest possible illustration of the principles underlying the process by which steel is made fit for use as a magnet.

When carbon is put into molten iron it immediately dissolves. There is no direct proof that the carbon first forms the carbide Fe_3C, which then becomes the solute substance in the molten iron, but the probabilities all seem to point that way. The best evidence that the molten iron, with the carbon in it, is a solution, is the fact that the temperature at which the liquid begins to solidify is progressively lowered as the proportion of carbon is increased.

The temperatures at which Delta changes into Gamma, and Gamma into Beta, show a similar gradual fall with increasing carbon. Making use of a method of illustration introduced by Roberts-Austen, all these temperature-changes may be shown as so many curves in a diagram, each curve marking the temperature boundary between different states in which the iron-carbon solution or alloy, carbon steel, can exist. The Roberts-Austen iron-carbon diagram in its entirety is a highly complex affair, and a perennial source of controversy among metallurgists, who are by no means agreed either as to how the diagram should be drawn or as to the interpretation of the facts it is intended to embody. In this paper, however, we are only concerned with the first and least contentious part of the diagram, where it relates to iron-carbon solutions containing amounts of carbon not exceeding one per cent, since magnet steels never contain more than that proportion. This part of the diagram is shown in Fig. 4, where all the boundary lines have been plotted from such observational data as are available at the present time.

In pure iron, solidification occurs at a critical temperature, but with the introduction of carbon the solidifying process becomes selective and extends over a wider and wider range of temperature as the percentage

* It need hardly be said that the discovery of hardening, which seems to imply a profound metallurgical knowledge, was made by accident. Some very primitive blacksmith, in a hurry to cool a piece of red-hot steel, plunged it into water, and simultaneously civilization took a long stride forward.

of carbon increases. This is illustrated in the diagram by the lines AL and AS, which mark the boundaries where solidification begins and ends respectively.

The temperature boundary where the iron changes from Delta to Gamma is approximately indicated by the line DY, which begins at the temperature determined by Wüst for pure iron, and passes through a point determined for the author by Mr. R. Rolfe for a steel containing 0·7 per cent of carbon. It has been assumed that as regards curvature this boundary line would resemble that between Gamma and Beta iron.

The boundary line GE shows where the iron, on

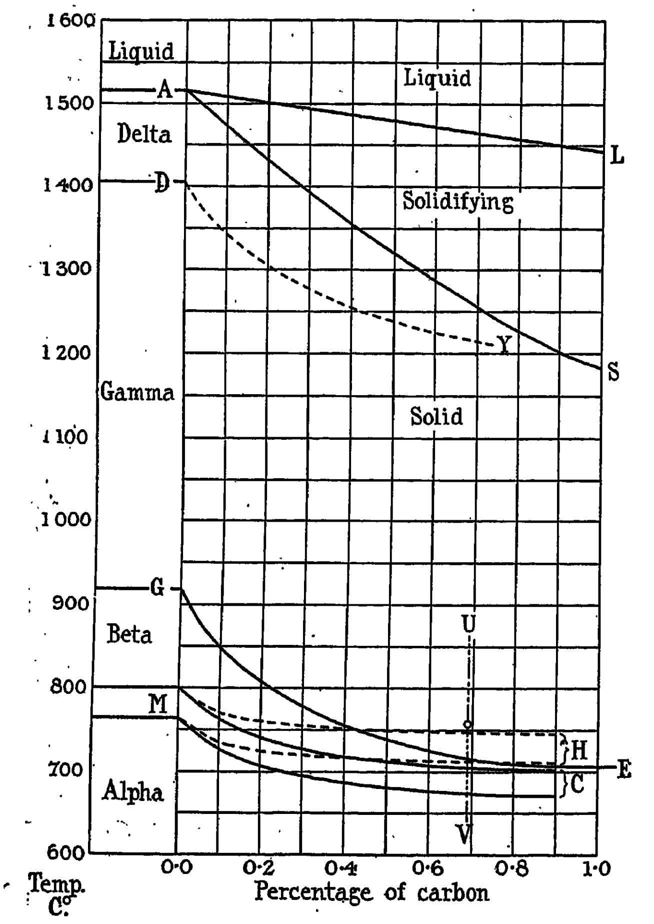

FIG. 4.—Roberts-Austen iron-carbon diagram, up to a carbon content of 1 per cent.

cooling, changes from Gamma into Beta. This line and the two solidification lines have been plotted from experimental data obtained by Carpenter and Keeling.*

Below the Gamma-Beta boundary are the diverging temperature zones, MH and MC, within which the Alpha to Beta and Beta to Alpha transformations occur during heating and cooling respectively. These have been plotted from curves, obtained by the author, representing the loss and recovery of magnetism. It will be noticed that with increasing carbon content the gradual lowering of the temperature of the Gamma-Beta transformation is so much greater than that of the Beta-Alpha or magnetic change, that the two phenomena begin to overlap when the carbon content is about 0·5 per cent. As the carbon is increased beyond that proportion and the extent of overlapping grows, it becomes increasingly difficult to secure experimental conditions that will result in a record of the two allotropic changes as distinct effects; with a falling temperature, for example, the heat emitted as the result of the Gamma-Beta change becomes only too easily merged in that associated with the Beta-Alpha transformation.

We are now in a position to follow the course of events as some particular specimen of carbon steel cools down and the iron passes in succession from Gamma to Beta and Beta to Alpha. The specimen chosen by way of example is one from which thermal and magnetic data have been obtained to illustrate this paper, being a pure carbon steel containing 0·687 per cent of carbon, by analysis. Steel of about this

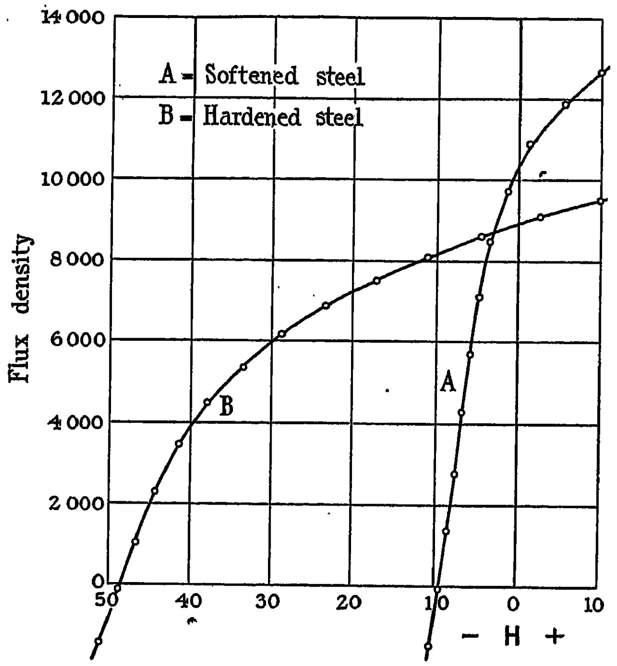

FIG. 5.—Demagnetization curves of pure carbon steel:—
Curve A, the steel in the softened state.
Curve B, the steel completely hardened.

carbon content makes a good magnet and represents the material commonly used for the purpose before the introduction of tungsten magnet steel. The two demagnetization curves given in Fig. 5 were obtained from a specimen of this steel, first in the softened condition and then in the hardened state. Curves of the loss and recovery of magnetism in the same steel are shown in Fig. 6, and it will be noticed at once that the introduction of carbon has not only lowered the general position of the curves on the scale of temperature, but also brought about a wide separation between the temperatures at which loss and recovery of magnetism occur.

* CARPENTER and KEELING: *Journal of the Iron and Steel Institute*, 1904, vol. 65, p. 224.

The rate of change of temperature with time, as the steel cools down through the Gamma-Beta-Alpha transformations, is shown in Fig. 7, where the rate of change of magnetic intensity and the corresponding portion of the time-temperature curve are also given,

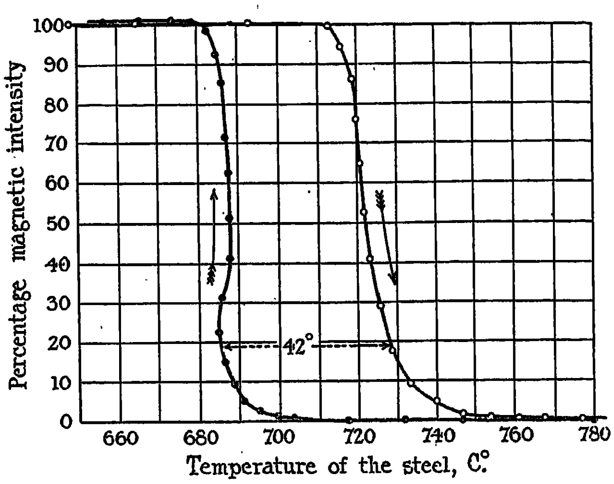

FIG. 6.—Loss and recovery of magnetism in pure carbon steel containing 0·687 per cent of carbon.

having solidified, the iron remains in the Delta state over a range of 30 or 40 degrees and then transforms itself into Gamma iron. In this state it remains over a wide range of more than 400 degrees. So far, nothing has happened that suggests any change in the steel as a solution. There does not appear to be any direct proof to be had, but it is universally believed that in the Gamma iron the carbon is still in solution and that the solute is the carbide of iron, Fe_3C. The cooling continues and at a temperature of 757° C., reading from Fig. 4, which is based on determinations by Carpenter and Keeling, or at 754° C. reading from Fig. 7, which contains the author's determination of the same point, the first sign of a departure from the normal rate of cooling makes its appearance; Gamma is beginning to be converted into Beta and the associated allotropic energy begins to be released as heat (Fig. 7). Three minutes later, at about 715° C., the first sign of magnetism appears, indicating the beginning of the change from Beta to Alpha. At about 5 minutes the completion of the transformation of Gamma into Beta is marked by the abrupt change, seen at P, in the course of the differential curve. At 11½ minutes the recovery of magnetism is complete, showing that the whole of the iron has been converted into Alpha iron.

Here we must stop to inquire what has become of

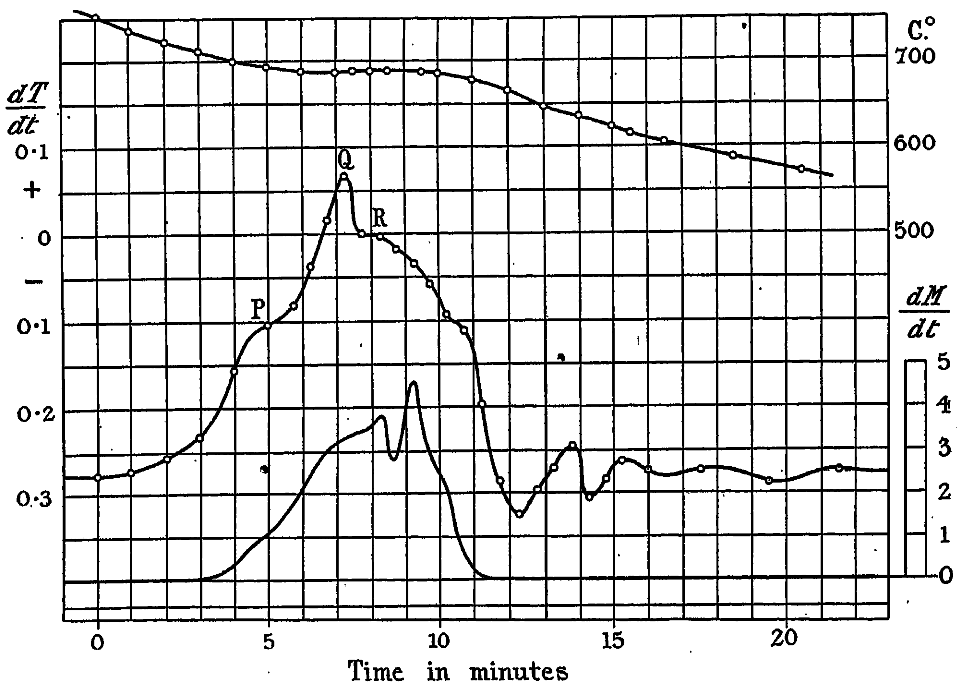

FIG. 7.—Pure carbon steel cooling from 900° C. Curves showing fall of temperature, departure from the normal rate of cooling consequent on the release of energy as heat (middle curve), and rate of change of magnetic intensity during recovery of magnetism.

all these observational data having been obtained concurrently. For convenience, the scale of time starts from the point where the differential curve first begins to depart from the normal course.

In Fig. 4 the cooling of the specimen of carbon steel is represented by the vertical line UV. The steel the surplus proportion of carbide of iron which is not soluble in Alpha iron. The total quantity of carbide in the steel being known, the surplus can only be ascertained if we can discover how much carbide is retained in solution by the Alpha iron. Information on this point is scanty and vague. Carbon steel, even

when softened, is much harder than pure iron, from which it may be inferred that it contains some carbide in solution, though not so much as there is in hardened steel. As to the amount, we have only the casual statement occasionally to be met with, that steel containing no more than 0·25 per cent or 0·30 per cent of carbon (for different amounts are named) cannot be hardened.* The statement is true enough, but presumably what it means is not that steel containing, let us say, 0·25 per cent of carbon is no harder than iron, but that when heated red-hot and plunged into water it is no harder than it was before. To anticipate a little, it is easy, by magnetic means, to ascertain approximately the amount of carbide in solution in steel "that cannot be hardened," and the amount that apparently dissolves in Alpha iron is found to correspond roughly with a carbon content of 0·26 per cent. Deducting that percentage from the total carbon content of the specimen of carbon steel, namely 0·687 per cent, the remainder, 0·427 per cent, represents the surplus carbide that is left with no available solvent when the whole of the iron has been converted from Beta into Alpha iron. Hence when that transformation takes place, the surplus carbide crystallizes out of solution, and in doing so the associated energy which went to create and maintain the state of solution is released as heat. The energy is considerable. In the present example it amounts to, roughly, 40 joules per gramme of steel, to which must be added about 6 joules per gramme for the energy released when Beta iron changes into Alpha. Altogether the energy released as heat was not far short of 50 joules per gramme of steel, the emission beginning at the third minute and spreading over about 8 minutes (Fig. 7). It is the emission of this heat, at an increasing rate, that gives rise to the extremely rapid variation in the rate of change of temperature which is noticeable in the curve in Fig. 7 between the points P and Q. The quantity of heat was sufficient to cause slight recalescence, the rise in temperature attaining a maximum at the point R.

The irregular oscillations in the curves in Fig. 7 may be just referred to in passing. They have their origin in experimental conditions for the most part, and proceed from thermal causes analogous to those which set up "hunting" in moving machinery. This sort of thermal hunting is seldom entirely absent in such experiments as these, and it is one of the many difficulties in the way of exact measurement.

The carbon steel specimen has now cooled down into the final stage in which the iron is wholly of the Alpha variety. Of the total amount of carbon in the form of carbide, namely 0·687 per cent, only 0·26 per cent remains in solution; the surplus 0·427 having crystallized out of solution because Alpha iron cannot in normal circumstances dissolve so much.

At this point it will be useful to recall the behaviour of a saturated solution of salt in water, in order to contrast it with the fundamentally different behaviour of steel as a solution. When the temperature of the salt solution is lowered the proportion of salt that is surplus at the lower temperature comes out of solution. Fall of temperature and quantity of surplus go together, and the amount of salt remaining in solution is solely a matter of temperature. In the course of these changes the solvent itself undergoes no modification; water it was, and water it remains. Contrast this with what happens in the steel, where it is the chameleon-like solvent that changes. It is converted from one kind of substance to another of a very different kind, from Beta iron to Alpha iron, and the surplus of solute arises from the fact that the carbide is less soluble in Alpha than it is in Beta; very much less soluble. Moreover, the amount of surplus is not governed by temperature, except within the narrow range where Beta is undergoing conversion into Alpha. Once that conversion is complete the surplus solute is a fixed quantum, the difference between the amount of carbide originally present in solution in the Beta iron, and the amount which Alpha iron can retain in solution as a system in stable equilibrium.

To create in the salt solution something analogous to the state of things in the steel, it would be necessary to endow the water with the power of transforming itself into, say, alcohol, and to suppose salt to be much less soluble in alcohol than it is in water. Then if, in a saturated solution of salt, the water happened to change into alcohol, the surplus salt would crystallize out of solution, just as the surplus carbide does when Beta changes into Alpha iron, and for the same reason. In a salt solution, such a transformation of the solvent as we have imagined would be regarded as an unexampled happening in a solution, yet when the change occurs in the solution called steel, metallurgical writers pass it over without so much as a hint to their readers that anything at all out of the way has taken place.

(9) Carbon Steel: The Quantity of Carbon in Solution and the Resulting Potency.

The relation between the carbon content and the Hopkinsonian coercive force of carbon steel in the hardened state was determined many years ago by Madame Curie * from a number of specimens of steel containing different proportions of carbon, the coercive force of each specimen being measured and the carbon content determined by analysis. The data so obtained, when plotted as co-ordinates, gave the curve which is reproduced in Fig. 8. The test specimens being in the hardened state, it may be assumed that the whole of the carbon was in solution as carbide of iron, and looking on coercive force as a measure of the potency of the steel, the curve gives the empirical relation between the proportion of carbide in solution and the resulting potency.

The reversed curvature of the carbon-coercive-force curve suggests that two opposing actions are at work, but of their nature nothing is known. There can be little doubt that a complete interpretation of the entire curve will one day be forthcoming, and when it appears it can hardly fail to throw light both on the mechanism of solution and on the molecular pattern that gives rise to potency in steel.

Meanwhile, the carbon-coercive-force curve is useful

* See, for example, Sauveur: "The Metallography and Heat Treatment of Iron and Steel," p. 295. (Sauveur and Boyston, Cambridge, Mass., U.S.A.)

* Mme. Curie: "Propriétés Magnétiques des Aciers Trempés," *Bulletin de la Société d'Encouragement*, 1898, vol. 3.

merely as a means for ascertaining one co-ordinate when the other is known. For example, by measuring the coercive force of a piece of softened carbon steel and referring to the curve (Fig. 8), the quantity of carbide of iron in solution is determined: a measurement that gives the solubility of the carbide in Alpha iron under conditions of equilibrium, provided the steel contains an excess of carbon. To soften the steel it would be sufficient to maintain it at a temperature of about 700° C. for 10 minutes, thus giving ample time for all the surplus carbide to pass out of solution, and leaving in solution only that quantity which is naturally soluble when the iron is in the Alpha state. The specimen of carbon steel referred to in Section (8) serves for a determination of this kind. The demagnetization curve (Fig. 5) for this steel in the softened state shows that the coercive force in that condition was 9·3. Reading from Mme. Curie's curve (Fig. 8), the corresponding carbon content is found to be about 0·26 per cent, or 27 molecules of carbide per 1 000 molecules of iron. From this it appears that 1 000 diatomic molecules of Alpha iron can retain 27 molecules of the carbide (Fe_3C) in solution; the surplus carbide, amounting in the present example to 44 molecules per 1 000 of solvent iron, having crystallized out of solution when the Beta iron changed into Alpha.

At the time Mme. Curie's experiments on carbon steel were made, the difficulty in ensuring identity in the composition of the magnetic test-piece and that of the sample chosen for analysis was not fully appreciated, and for this reason the curve reproduced in Fig. 8 must be regarded as no more than a good approximation. Nevertheless, Mme. Curie's observational data demonstrate conclusively that the relation between carbon content and coercive force in hardened carbon steel is expressed by a curve of reversed curvature, an *S*-shaped curve. In the following section we shall see that just as the solute molecule Fe_3C in carbon steel results in a curve of *S* shape, so other solute molecules of the potency-giving kind give rise to curves of similar shape.

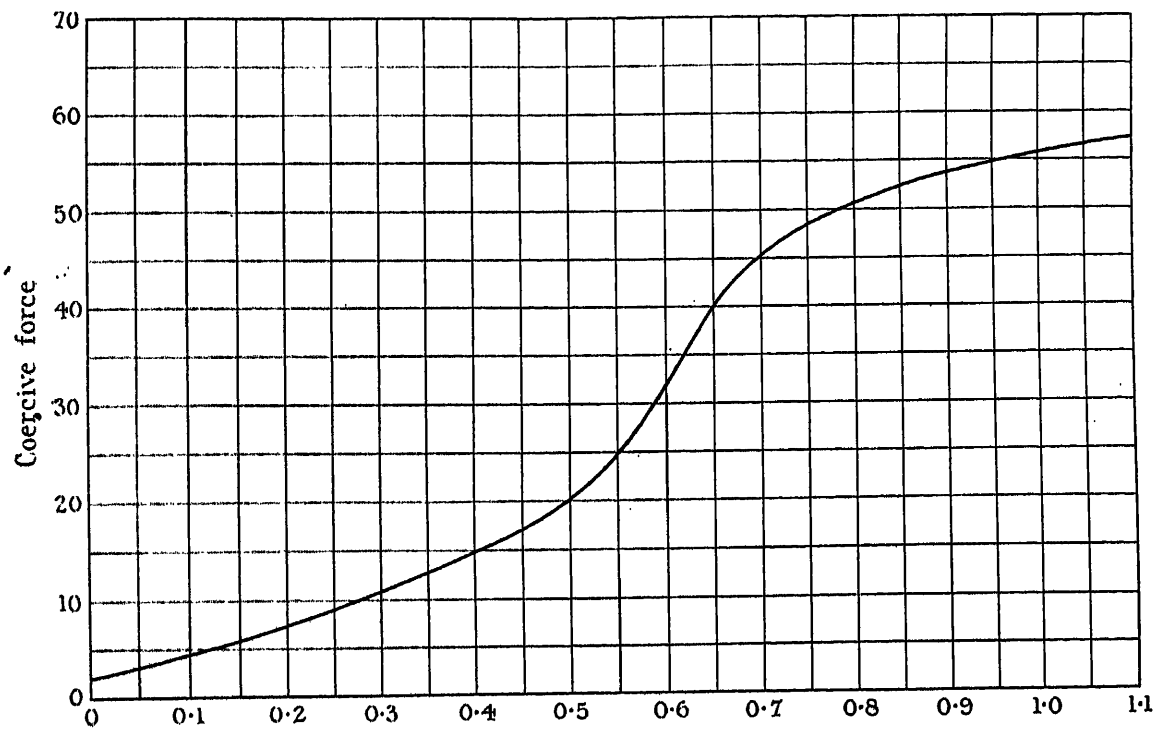

FIG. 8.—Pure carbon steel in the hardened state. Relation of coercive force to carbon content. (Mme. Curie.)

(10) Tungsten Steel: The Carbides and Coercive Force.

Tungsten magnet steel might be described as carbon magnet steel in which about half the carbide of iron has been replaced by carbide of tungsten, the total content of carbon remaining unchanged. The effect of this part replacement of one solute substance by another is to increase the Hopkinsonian coercive force from rather less than 50 to rather more than 70, and this increase in potency leads to a large increase in the magnetic energy which the hardened steel can maintain, the useful energy being about 7 200 ergs per cm^3 for carbon steel and as much as 14 000 ergs for good tungsten steel. This improvement in useful effect is all the more remarkable because carbide of tungsten by itself is unable to accomplish it; it needs the cumulative action of both the carbides.

Quite apart from the significance of the changes in the magnetic properties of steel that follow the intro-

duction of tungsten, metallurgists have been, and probably still are, divided in opinion as to the composition of the carbon compounds in tungsten steel. There seems, however, hardly room to question the conclusions arrived at by Arnold and Read from their analyses of the carbide residues of tungsten steels in the softened state. Assuming their interpretation to be correct, the formation of the series of compounds found in tungsten steel may be briefly described as follows: We shall begin with a mass of pure iron containing N atoms of iron, the quantity being defined symbolically as NFe. If x atoms of tungsten are added to the mass, they combine with $2x$ atoms of iron as the tungstide of iron Fe_2W, a compound which dissolves in the remaining iron. The solution so formed is represented by $(N - 2x)\mathrm{Fe} + x\mathrm{Fe_2W}$. We now add y atoms of carbon to the solution, and tungsten having a greater affinity for carbon than for iron, y atoms of tungsten leave the tungstide of iron in order to combine with the carbon as the carbide of tungsten WC. This sets free $2y$ atoms of iron, and hence the solution is now

$$(N - 2x + 2y)\mathrm{Fe} + (x - y)\mathrm{Fe_2W} + y\mathrm{WC},$$

the carbide of tungsten dissolving in the iron.

By increasing the quantity of carbon, we next arrive at a stage when the proportion of carbon to tungsten, by weight, is that of the atomic weights of the two elements, namely 12 to 184. With this proportion the quantity of carbon just suffices to combine with the whole of the tungsten. That is to say $y = x$, the whole of the tungstide of iron having been decomposed. The solution is now $N\mathrm{Fe} + x\mathrm{WC}$, being solely carbide of tungsten dissolved in iron. To this solution we now add some more carbon. The additional carbon combines with some of the iron as the carbide of iron Fe_3C, and if the number of carbon atoms added in this way is z, then the solution will be represented by $(N - 3z)\mathrm{Fe} + x\mathrm{WC} + z\mathrm{Fe_3C}$, both the carbides dissolving in the iron. This last formula represents the composition of tungsten magnet steel, and in good magnet steel z is approximately equal to x; that is to say, the number of molecules of carbide of iron is roughly equal to the number of molecules of carbide of tungsten. Since each solute molecule contains one atom of carbon, equality in number of molecules corresponds with equality in weights of carbon, equality in percentage weights.

Two points should be noticed before going on. First, that although carbon combines easily with iron, yet when put into iron which already contains tungsten, it combines with the tungsten in preference to the iron and only combines with the iron when all the tungsten has been utilized. Evidently carbon has a greater affinity for tungsten than it has for iron. This fact has an important bearing on the spoiling of tungsten magnet steel, a subject treated in Sections (13) and (14).

The second point is one which deserves more attention than it has received from metallurgical writers. The carbide residues on which Arnold and Read founded their conclusions were obtained from steels in the softened state in which, of course, the iron was of the Alpha variety. It seems to be tacitly assumed that the particular carbon compounds proved by analysis to be present in Alpha iron at room temperatures, must also be present as identically the same compounds in Beta iron or Gamma iron at the high temperatures at which those allotropic varieties exist. The assumption is probably correct, but it would be more satisfactory if a proof of some kind could be found.

In what follows it will be assumed, for the present without proof, that if the compounds WC and Fe_3C are present in Alpha iron then they must have been present also when the iron was in the Beta, the Gamma and the Delta states, present as identically the same compounds.

Assuming the existence of the two carbides WC and Fe_3C as the active solute substance in hardened tungsten magnet steel, it would be useful to know how and in what degree those solute molecules contribute to the potency of the steel. What is needed is a graph for tungsten steel expressing the relation between the carbon content and the coercive force, after the manner of Mme. Curie's curve for carbon steel. Some years ago the present writer would have said that observational data for the preparation of such a graph existed in abundance. Numerous experimenters having published the values they had obtained for the coercive force of specimens of tungsten steel of widely varying composition, it seemed that it should only be necessary to bring those values together and the relation of carbon content and coercive force would be disclosed once for all. But on plotting various tests of the kind, culled from many sources, astonishing discrepancies became apparent in the results of different observers and even in those of the same observer. Not even an approach to systematic arrangement could be discovered, and it became evident that to establish the required relation it would be necessary to investigate afresh from beginning to end. This the author determined to do and the necessary experiments were put in hand. Many unforeseen difficulties were encountered, and it was only after several years of continuous research that the work was brought to a successful conclusion in the spring of 1923.

A previous attempt of the kind had been made by Dr. Swinden * to establish the relation between carbon-content and coercive force in steel containing about 3 per cent of tungsten, but the wide discrepancies in the observational data, partly attributable to the use of the magnetic balance of Du Bois, partly to other causes, completely masked the underlying law.

In the author's investigation all the samples of steel contained the same percentage of tungsten, which was that commonly used in magnet steel at the present time, namely 6 per cent. The carbon content of the samples varied step by step from about 0·06 per cent up to 1·3 per cent. All the magnetic tests were made with an astatic moving-coil magnetometer giving direct readings, by mirror and scale, of the applied magnetizing field and the resulting intensity of magnetization. Test-pieces of ellipsoidal form were used throughout the research, in order to avoid the ambiguities so frequently introduced into magnetometer

* T. Swinden: "The magnetic properties of a series of carbon-tungsten steels," *Journal I.E.E.*, 1909, vol. 42, p. 641.

work by the use of cylindrical test-pieces. On the whole the accuracy of the magnetic tests was in excess of what was needed, being considerably greater than the accuracy attained in the analysis of steel.

The distribution of carbon in a bar of rolled steel is seldom uniform, and in testing pieces of steel taken from a bar it is always a matter of uncertainty whether the carbon content of the piece used for the magnetic identity in carbon content was removed, and it was only by the adoption of this method throughout the final tests that consistent results were secured.

Ordinary chemical analysis only gives the percentage quantities of the various elements in the steel; it does not indicate whether and in what way the elements are combined, and there is nothing to show whether the carbon, for example, is present as a carbide

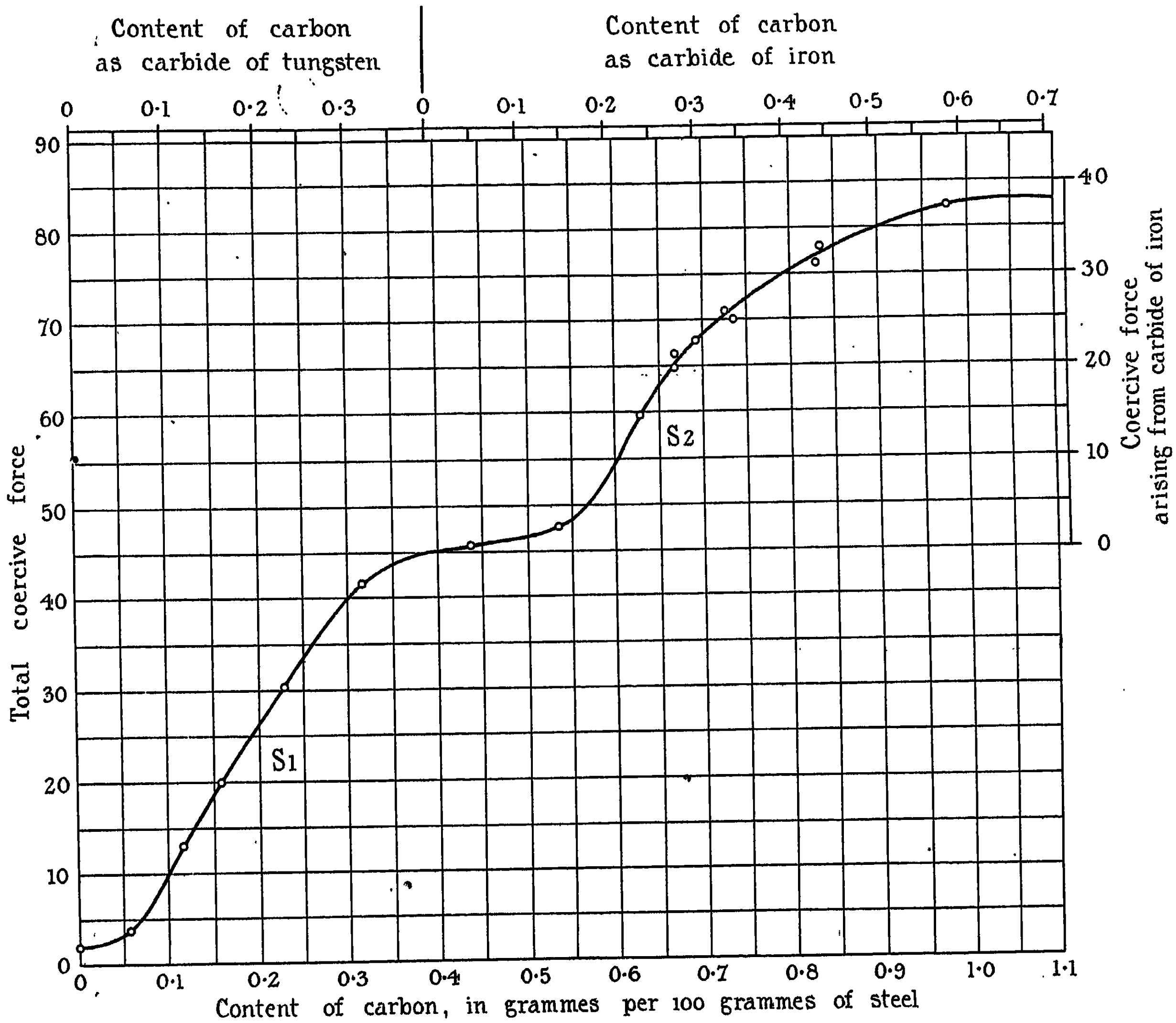

FIG. 9.—Tungsten magnet steel in the hardened state, the steel containing 6 per cent of tungsten. Relation of coercive force to carbon content.

tests is identical with that of the sample chosen for analysis. In the preliminary tests many errors were traced to this cause although the greatest care had been taken to avoid them by choosing, as the samples for analysis, portions of the rolled bar immediately adjacent to the ends of the magnetometer test-piece. The procedure finally adopted was to prepare the magnetometer test-piece and then, after the completion of all the necessary magnetic tests, to analyse the test-piece itself. In this way all chance of error from want of or not. Now tungsten steel and cobalt steel are very rarely free from a defect described in a later section under the heading spoiled steel. In spoiled magnet steel, the carbide compounds are partially decomposed and therefore more or less ineffective as solute molecules of the potency-creating kind. In short, loss of potency, as the result of spoiling, is the rule.

This prolific source of error runs through all previous work on tungsten magnet steels, and is largely responsible for the extraordinary discrepancies in the results obtained

by so many different observers. It was essential to avoid it, and this was done by making use of the method of restoring spoiled steel described in Section (13). Some of the samples were obviously in need of restoration, others were practically unspoiled; but to be on the safe side every sample was subjected to the process of restoration, whether it appeared to need it or not, this being done before making the magnetometer test-pieces. All the test-pieces were hardened by quenching them in an aqueous solution of calcium chloride from a temperature of 850° C.

The final outcome of this prolonged investigation * is recorded graphically in Fig. 9 as a curve connecting percentage carbon content with coercive force in hardened steel containing 6 per cent of tungsten. It is at once apparent that the introduction of tungsten, which we have assumed to result in the presence of the two carbides WC and Fe_3C, gives rise to two *S*-shaped curves, S1 and S2, following one after the other.

The proportion of carbon needed to combine with 6 per cent of tungsten as WC is, of course, 6 multiplied

TABLE 1.

Carbon content		Carbon steel		Tungsten steel		Gain and loss of coercive force
	Per cent	Carbide	Coercive force	Carbides	Coercive force	
1st portion	0·39	Fe_3C	14·2	WC	45·0	30·8 +
2nd portion	0·33	Fe_3C	32·8	Fe_3C	25·4	7·4 –
Totals	0·72		47·0		70·4	23·4 +

Gain and loss of potency in magnet steel containing 0·72 per cent of carbon, when about half the carbide of iron is replaced by tungsten carbide.

by the ratio of atomic weights, namely 12/184. The required proportion is therefore 0·391 per cent, and on referring to Fig. 9 it will be seen that 0·39 per cent of carbon corresponds quite well with the point of inflexion where curve S1 ends and curve S2 begins. This is conclusive as to the origin of curve S1. The increasing potency, measured by coercive force, manifestly arises from the gradual introduction of molecules of carbide of tungsten, and the curve necessarily comes to an end at the point where the quantity of carbon just suffices for 6 per cent of tungsten. This, so far as the author is aware, is the first definite proof of the existence of the carbide of tungsten WC in hardened tungsten steel, and it is worth noting that the fact is established from magnetic data.

Curve S1 being clearly accounted for by the presence of carbide of tungsten, the second curve, S2, must arise from the balance of carbon in excess of 0·39 per cent, and we may assume that it is in the form of carbide of iron, Fe_3C. Scales have been added in Fig. 9 giving the percentage of carbon and the coercive force for curve S2 separately, for convenience in computing the coercive force of tungsten magnet steels.

Carbon, when added to steel which already contains carbon in the form of carbide of tungsten, is not so effective in creating potency as it would be if added to steel containing the same quantity of carbon as carbide of iron. For this reason the gain in potency, consequent on the replacement of some of the carbide of iron by tungsten carbide, is partly set off by a loss of potency due to the diminished effectiveness of carbide of iron in tungsten steel. An example of this is given in Table 1 for steel containing 0·72 per cent of carbon, the total being divided into two portions, the first amounting to 0·39 per cent, and the second to 0·33 per cent. It will be seen that the gain of 30·8 units of coercive force, due to the introduction of 6 per cent of tungsten, is set off by a loss of 7·4 units as the result of the decreased efficacy of the carbide of iron. The table has been prepared from Mme. Curie's curve for

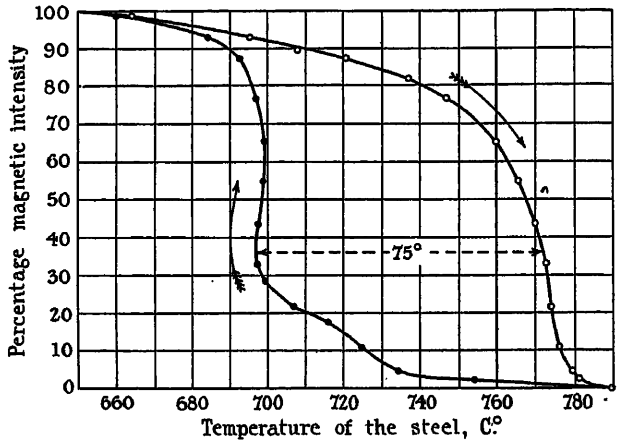

FIG. 10.—Loss and recovery of magnetism in tungsten magnet steel.

carbon steel and the author's double curve for tungsten steel.

It follows from the form of the curves S1 and S2 in Fig. 9, that in a steel containing somewhere about 0·72 per cent of carbon the content of tungsten may be varied considerably without materially affecting the coercive force, there being a certain degree of give and take about the two curves. This inference is borne out in practice, for the content of tungsten may be varied from about 5 per cent to about 6·5 per cent without causing any material change in coercive force.

It may be anticipated that when the shape of Mme. Curie's curve for carbon steel has been interpreted, the explanation of the two curves in series which express the relation of Hopkinsonian coercive force to carbon content in tungsten steel will also be forthcoming. These two curves have an immediate practical use, however, for since they represent restored—that is to say unspoiled—tungsten magnet steel, a comparison of the analysis of any particular batch of tungsten steel with the ordinates of the curves indicates at once the degree of spoiling, or decomposition,

* Work on the samples of steel was held in abeyance for over a year pending the discovery of an entirely trustworthy method of restoration.

as measured by the deficiency in coercive force. The author has also made use of the curves in Fig. 9 for another purpose, which will be referred to in Section (14).

The temperatures at which the several allotropic changes take place in tungsten steel are known to be so nearly the same as those determined for carbon steel that the iron-carbon diagram, of which a portion has been given in Fig. 4, serves well enough for tungsten steel. One reservation must be made, however. It has already been shown in Fig. 6 that in carbon steel there is a wide temperature difference between the curves of loss and recovery of magnetism. In tungsten steel of the same carbon content the difference of temperature between loss and recovery of magnetism is much greater, as will be seen on referring to Fig. 10. Hence to represent tungsten steel the iron-carbon diagram given in Fig. 4 would need a modification in the position of the temperature zone in which the transformation from Beta iron to Alpha occurs, the separation of the zone of loss of magnetism from the zone of recovery being roughly 42 degrees C. for carbon steel, and about 75 degrees C. for tungsten steel, when both steels contain 0·70 per cent of carbon.

(11) Pressure as the Force which Controls the Magnetic Change.

The zones of temperature in which the allotropic changes take place from Alpha iron to Beta, and vice versa, are indicated in diagrams representing the loss and recovery of magnetism. Examples have been given in Figs. 3, 6 and 10, showing the magnetic change in pure Swedish iron, carbon steel and tungsten magnet steel. In any kind of steel, and in most specimens of iron, there is a noticeable interval, on the scale of temperature, between the zone where magnetism is lost on heating and the zone where it is regained on cooling, recovery of magnetism occurring at the lower temperature. The existence of a temperature interval has been known for a generation or more, and it has been supposed that loss and recovery of magnetism in the magnetic elements necessarily occur at different temperatures.* That loss and recovery of magnetism are nearly always separated by an interval of temperature, recovery taking place at the lower temperature, does not admit of doubt, but the fact has remained without explanation and the forces which determine the position of the magnetic change on the temperature scale have so far remained unidentified.

To-day, however, the facts are better known. The experiments with Swedish iron, of which a typical example is recorded in Fig. 3, have shown that when the iron is sufficiently free from other elements the zone where magnetism is regained on cooling coincides with the zone where it is lost on heating. It follows that the separation commonly observed between loss and gain arises from the presence of foreign elements in the iron, and this being granted there is no difficulty in attributing the separation seen in Fig. 6 to the carbon, and the wider interval in Fig. 10 to the presence of tungsten in addition to carbon. In both these examples the foreign elements are known to form compounds which dissolve in the iron, and this at once suggests the possibility that the interval between loss and gain of magnetism has something to do with solution. Guided by these deductions from experiment it seems possible to account in a simple way for the lowering of the temperature at which magnetism is recovered when iron contains elements or compounds in solution. In its present tentative form the explanation does not account for all the facts, but it may be given here because it has grown naturally out of the ideas on which this paper is founded, and seems to provide a clue which may be usefully followed in future research.

* See, for example, Ewing, 2nd edn., chap. 6, pp. 178–179.

We assume that, so far as magnetism is concerned, the iron molecule of two atoms behaves as though each atom were a tiny coil or current ring carrying a constant electric current, thus accounting for the constant magnetic moment and magnetomotive force which the iron atom is known by observation to possess. To simplify the problem as much as possible, we may imagine the two current rings to be separated by a fixed distance and that each is free to turn about a diameter. For this electromagnetic system the only position of stable equilibrium is that in which the two rings are in parallel planes with their currents flowing in the same sense. In that position the magnetomotive forces of the two current rings act in the same direction, the system possesses a magnetic moment, and the two rings represent the electrical system of an iron molecule in the magnetic or Alpha state. To convert the molecule into the non-magnetic form, the aspect of the two current rings with regard to each other must be reversed (by a movement equivalent to turning one of them round through half a revolution) so that their currents flow in opposite senses. In this condition, which is one of unstable equilibrium, the two magnetomotive forces will be in opposite directions and the system will have no resultant magnetomotive force and no magnetic moment. In short, when the two current rings are back to back, as it were, they represent the iron molecule in its non-magnetic form.

In undergoing the change from the magnetic to the non-magnetic state the system of two current rings passes from stable equilibrium to unstable equilibrium and force must be applied to effect the change. Moreover, if the force is withdrawn or reduced below a certain critical value, the system will at once revert to the magnetic state of stable equilibrium. In other words the two current rings, in virtue of their electric currents, exert forces on each other which constantly tend to cause them to revert to the magnetic arrangement—a statement which is equally true of any system of electric circuits carrying constant currents. We may therefore regard the iron molecule as an electrical system endowed with a *force of reversion* which, if it is not balanced by an opposing force, will cause the molecule to assume its magnetic form. From this point of view it will be seen that when an iron molecule retains the non-magnetic form it must be because the inherent force of reversion is outweighed by some opposing force, and if the opposing force should diminish until the balance of forces turns the other way, then the molecule would revert to the

magnetic form. As to the nature of the opposing force, the phenomena of the magnetic change point unmistakably to one characteristic. For at any temperature below the region of the magnetic change all the iron molecules are magnetic, and above that region they are all non-magnetic. Hence, whatever the opposing force may be, it is clearly one which acts indiscriminately on all the iron molecules, and in seeking for it we must look for some force of a general kind capable of acting equally on every molecule throughout a solid mass.

We proceed on the supposition that inside any solid body there is a pressure arising in the same way as the pressure in a gas, proportional to the absolute temperature but no doubt depending on more complicated factors than those governing the simple law of gas pressure. In pure iron this temperature force will be the only pressure at work, but when any substance, either elementary or compound, is dissolved in the iron there will be an additional general force, the pressure of solution. The purist may perhaps say that these two sources of pressure cannot be distinguished from one another, but for mental convenience we shall regard heat pressure and solution pressure as separate components, the total pressure acting in the iron or steel being the sum of the two.

Our next step is to jump to a conclusion, by assuming that the total pressure is the force acting in opposition to the force of reversion inherent in the iron molecule. On this assumption, so long as the total pressure exceeds the reversion force, every iron molecule throughout the mass will be compelled to remain in the non-magnetic state; but when, for any reason, the opposing force of pressure falls to a value at which it is outweighed by the reversion force, then every iron molecule will revert to its magnetic arrangement. How the complex forces hidden in the word "pressure" are brought to bear on the electrical system of the iron molecule so as to act in opposition to the inherent force of reversion, we do not know. This, and much more, is at present far beyond our ken. But if we adopt the hypothesis that what is called pressure in some mysterious way controls the iron molecule in its magnetic changes, then it will be found that the facts disclosed by the curves which represent loss and recovery of magnetism arrange themselves in a more or less orderly fashion.

To begin with pure iron. Here the only pressure is that arising from temperature. Raise the temperature of a piece of Alpha iron, that is to say, increase the pressure, and at a certain point the rising pressure will outweigh the reversion force of the iron molecules. Accordingly the iron will be compelled to transform itself into the non-magnetic form, and at any temperature above the critical zone in which the change occurs every molecule in the piece of iron will be forcibly held in the non-magnetic form by the preponderating force arising from the heat pressure.

The iron being now in the non-magnetic state, let the temperature be lowered. There will be a corresponding fall in the heat pressure and, as the falling temperature traverses the critical zone, the diminishing pressure will be outweighed by the reversion force and the iron will therefore return to the magnetic state. That is to say, above the critical zone the pressure exceeds the reversion force, and below it the reversion force outweighs the pressure; and since in pure iron the only source of pressure is the temperature, the change from one state of things to the other must take place within the same critical zone of temperature whether the change is from magnetic to non-magnetic or the other way about. This is in agreement with the experiment recorded in Fig. 3.

Now consider the case of iron with something dissolved in it, so that in addition to the heat pressure there will be the pressure arising from the state of solution. We may take carbon steel as an example. Disregarding the peculiar action of carbon in creating the molecular pattern that gives carbon steel its potency, attention must be confined to the fact that carbon forms a soluble compound which dissolves in the iron and therefore gives rise to solution pressure. It will be convenient to begin by supposing that the steel is cooling down from a temperature at which the solvent iron is in the non-magnetic state, so that the conditions governing the pressure may be noted as the temperature falls.

It may be taken for granted that the strength of the electromagnetic forces at work within the iron molecule will not be affected by the mere presence of neighbouring solute molecules, and consequently the critical pressure at which reversion to the magnetic state will occur as the metal cools, should be the same in the carbon steel as it is in the iron. But in the steel the pressure is augmented by the solution pressure, and hence, when the temperature has fallen to the point at which pure iron reverts to the magnetic state, the total pressure in the steel will exceed the reversion force by the amount of the solution pressure and the iron molecules will therefore still be held in the non-magnetic state. To bring about reversion to the magnetic state the total pressure must be reduced to the critical value, and this can only be done by lowering the temperature so as to neutralize the increment of pressure due to solution by a corresponding decrement in the heat pressure. In other words, when iron contains anything in solution so as to give rise to additional pressure, the temperature at which reversion to the magnetic state occurs must necessarily be lower than the temperature of the magnetic change in pure iron. This deduction, also, is in agreement with observation.

Small variations in the temperature at which the magnetic change occurs in successive tests of the same specimen of iron are frequently observed, the critical temperature often rising three or four degrees with each succeeding test. Discrepancies of this kind are readily explained as the result of small changes in the total pressure. Gases of different kinds dissolve freely in molten iron and a good deal of gas may remain in solution in the cold metal. Each time the specimen is heated some of the gas is likely to escape. The result would be a small reduction in the solution pressure and a corresponding rise in the temperature required to bring the total pressure to the critical value.

A striking example of the effect which dissolved

gas may have in lowering the temperature of the magnetic change came under the author's notice when investigating a sample of ingot iron; iron of quite exceptional purity and free from all but a mere trace of carbon. Much to the surprise of the experimenter, the mean temperature of the zone of the magnetic change was found to be 756° C., an extraordinarily low value for iron free from impurities. Judging from numerous specimens of pure Swedish iron, the mean temperature of the magnetic change in pure iron is 780°, or possibly three or four degrees higher. In the case of the ingot iron, therefore, there is a lowering of at least 24 degrees to be accounted for. There can be little doubt as to the cause. The intention in making ingot iron is to obtain the greatest possible purity and, more particularly, to eliminate carbon. For that purpose the molten metal is "washed" with oxygen, a process which affords ample opportunity for the gas to dissolve in the iron. The metal when cold may be described as a saturated solution of oxygen in pure Alpha iron, and it is to the pressure arising from this state of solution that we may attribute the lowering of the temperature of the magnetic change by 24 degrees.

The most remarkable example of the effect of solution in lowering the temperature at which magnetism is recovered on cooling is afforded by the nickel-iron alloy discovered by Hopkinson.* The true composition of the alloy appears to be exactly one part of nickel to three parts of iron. The magnetic change of any mixture of these two metals would naturally be expected to occur somewhere between the temperatures of the allotropic change in iron and in nickel, that is to say between 780° and about 350° C. In any case it would not occur below the latter temperature, even if nickel alone determined the magnetic change. But Hopkinson's experiments showed that with any proportions of nickel and iron the point at which magnetism was regained was very considerably below 350° C., and from this it was clear that the metals formed an alloy. It was found, moreover, that the amount by which the temperature of recovery of magnetism was lowered grew suddenly to a sharply defined maximum when the proportions of the metals were exactly one to three, the recovery of magnetism then taking place at about 50 degrees below 0° C.

The existence of a maximum implies that one part of nickel and three of iron form a definite alloy possessing distinctive properties, and among other qualities solution pressure would presumably attain a maximum value. It seems very probable that in such an alloy—a mutual solution of two metals—the pressure of solution would be far greater than it is when a fractional percentage of carbon is dissolved in iron, and on the pressure hypothesis the much higher solution pressure would necessitate a much lower temperature for the recovery of magnetism. All this accords well with the fact that the temperature of magnetic recovery in the nickel-iron alloy is lowered to an extraordinary extent.

From the above examples of the recovery of magnetism it appears that the pressure hypothesis, founded on the supposition that the electrical system of the iron molecule behaves like a system of coils or current rings, agrees well with what is known about the varied temperatures at which magnetism is regained on cooling.

Turning to the converse problem, loss of magnetism in iron which contains other elements, the outstanding fact is the interval which separates the temperatures at which magnetism is lost and regained, the temperature difference between loss and gain varying from a few degrees when a little carbon is dissolved in the iron, to many hundred degrees when iron and nickel are mutually dissolved in each other. For ease of comparison the curves of magnetic loss and recovery for pure iron, carbon steel, tungsten steel and the

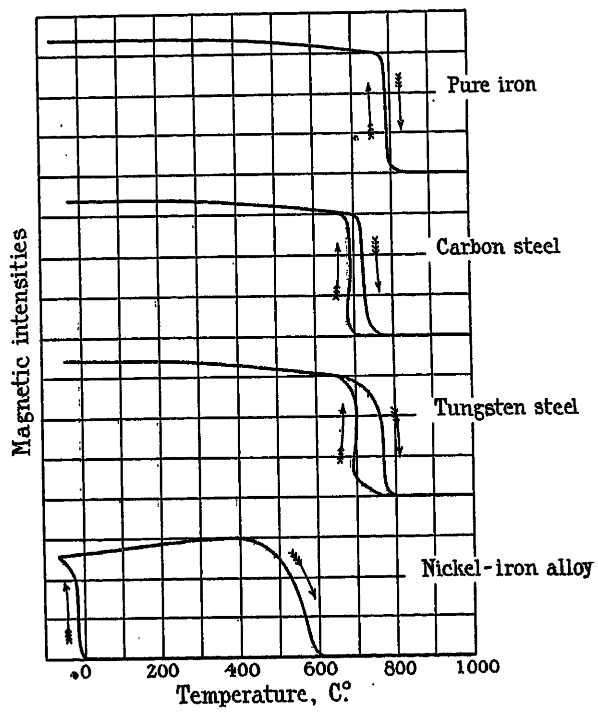

FIG. 11.—Comparison of loss and recovery of magnetism in pure iron, carbon steel, tungsten magnet steel and nickel-iron alloy.

nickel-iron alloy have been brought together one under the other in Fig. 11. In these curves it is noticeable that although the temperature at which magnetism is lost varies to some extent, yet in the main the separation between loss and recovery is brought about by the lowering of the temperature at which magnetism is recovered.

So far as the carbon steel is concerned, the temperature separation between loss and gain of magnetism is readily accounted for on the pressure hypothesis. When magnetism has been regained, that is to say when all the solvent iron has reverted to the Alpha state, any surplus carbide passes out of solution. This decreases the pressure and causes the total pressure to fall well below the critical value which brought about the recovery of magnetism. To compel the iron to become non-magnetic once more, the total pressure

* J. HOPKINSON: *Proceedings of the Royal Society*, 1889 and 1890. The principal results will be found in EWING, 2nd edn., chap. 8.

must be brought up to the critical value, and to do that the temperature must be raised. If the whole amount of carbide passed out of solution, reducing the solution pressure to zero, the required critical pressure would only be attained when the temperature reached the zone where pure iron loses its magnetism. But we know that the whole of the carbide does not pass out of solution when the solvent iron assumes the Alpha form. Roughly one-third of it remains in solution and, consequently, there is still a solution pressure although it is, of course, much reduced. Taking the reduced solution pressure into account, it is clear that the critical pressure should be attained at a temperature well above the zone of recovery, but certainly below the zone of the magnetic change in pure iron. Hence loss of magnetism may be expected to occur at a somewhat lower temperature in the carbon steel than it does in pure iron, and a reference to Fig. 11 shows that this is in fact what happens.

In tungsten steel the fact that loss of magnetism takes place well above the temperature of recovery is to be explained in the same way. But in this case there are discordant features for which the pressure hypothesis as it stands offers no satisfactory explanation. Apparently some factor has been left out of account, and to explain the behaviour of tungsten steel it seems necessary to assume that, for any given quantity of solute, the solution pressure in Alpha iron is less than that in Beta iron. Again, in the nickel-iron alloy where, on the face of it, nothing passes out of solution when the two elements undergo their transformation from the non-magnetic to the magnetic state, our hypothesis can only explain the wide separation between recovery and loss of magnetism on the supposition that the solution pressure of an alloy of Alpha nickel with Alpha iron is ever so much less than that of the Beta nickel with Beta iron alloy. Independent evidence on the point is wanting and there is therefore nothing either for or against the idea that solution pressure may differ according to whether magnetic molecules are in their Alpha state or their Beta state.

One other matter deserves notice connected with the magnetic change in steels which contain more carbon than is freely soluble in Alpha iron. In such cases the curves of loss and recovery of magnetism frequently differ in their slope, the recovery curve being more upright than the curve of loss. This agrees well with the pressure hypothesis and it can be shown that, of the two curves, it is the curve of loss which truly represents the normal progress of the transition from one state to the other, the curve of recovery being liable to distortion.

Here, for the present, the pressure hypothesis must be left. It affords but a partial explanation, marshalling some facts in their order, leaving others unexplained. Complete agreement was not to be expected, for to apply to solid steel the simple ideas about pressure which we derive from the behaviour of gases, is to ignore the effect of the want of molecular freedom in

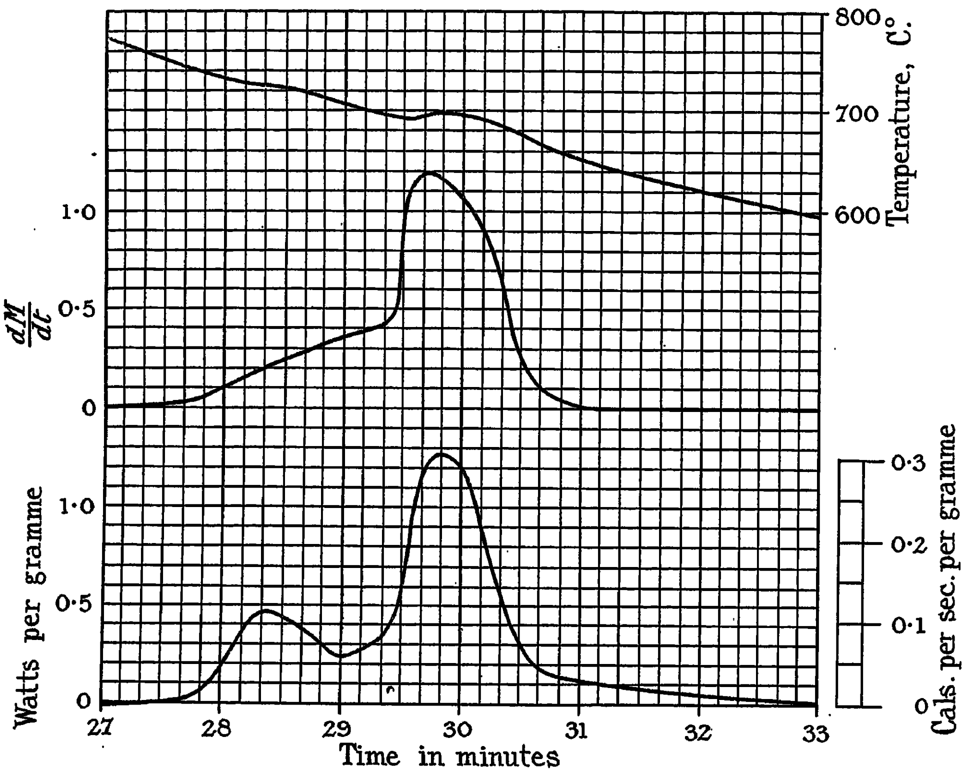

FIG. 12.—Release of energy when tungsten magnet steel cools from 900° C. Curves showing fall of temperature, rate of change of magnetic intensity during recovery of magnetism, and the rate at which energy was released as heat.

the solid. But on the supposition that the electromagnetic forces inherent in the electrical system of the iron molecule naturally cause it to revert to the magnetic state, the idea that pressure acts in opposition to the force of reversion seems to hold the promise of a rational explanation of the relation between temperature and the magnetic change.

(12) The Energy Released in Tungsten Steel on Cooling Down.

The sequence of events as tungsten magnet steel slowly cools down, and the molecules of iron pass from Gamma to Beta, and Beta to Alpha, is illustrated in a novel way in Fig. 12, where in place of the customary inverse-rate curve, or a time differential curve similar to the one already given for carbon steel (Fig. 7), the actual rate of release of energy is given in joules per

Table 2.

Allotropic change	Energy per gramme of steel: Joules	Energy per gramme of steel: Calories
Gamma iron to Beta iron	26·4	6·3
Beta iron to Alpha iron	5·9	1·4
Transfer of carbide from solution to crystal	47·9	11·4
Reversal of the Precursor effect ..	18·6	4·5
Totals	98·8	23·6

Allocation of the allotropic energy released during the cooling of tungsten magnet steel ($C = 0 \cdot 65$; $W = 6 \cdot 0$) from 900° C., the tabular figures being obtained by integration of the energy curve in Fig. 11.

Note.—As determined from Fig. 11, the energy released when Gamma iron changes into Beta is 6·3 calories per gramme of *steel*. This corresponds with 6·85 calories per gramme of *iron* in the steel, a figure which compares with the value determined by Wüst from calorimeter tests of pure iron, namely 6·67 calories per gramme.

second (watts) per gramme of steel, thus for the first time presenting the facts in a quantitative form. The ordinates of the energy curve have been computed by the author from data obtained by concurrent observations of the temperature of the steel test-piece and the difference of temperature between the test-piece and the walls of the furnace, making use of the radiation formula:—

$$\frac{dE}{dt} = \frac{ra}{m}(T_2^4 - T_1^4) + s\frac{dT_2}{dt}$$

Here E denotes energy, T stands for absolute temperature, r is the radiation constant, a the superficial area of the test-piece and m its mass. The specific heat of the steel, which is of course a variable, is denoted by s.

The released energy, represented by the area of the graph in Fig. 12, comes from four sources, namely (1) the change from Gamma to Beta, (2) the change from Beta to Alpha, (3) the passage of the surplus carbide molecules from solution to crystal, and (4) the energy previously absorbed by the precursor effect and given out again on cooling. Although there is some overlapping, it is possible to separate the whole quantity of energy into its components, as shown in Table 2. To engineers who think in kilowatt-hours, 98·8 joules per gramme conveys nothing, until it is discovered that the energy is equivalent to nearly 28 kilowatt-hours per ton of steel.

It will be noticed in Fig. 12 that the carbides present in the steel began to come out of solution at the 29th minute of the experiment and that by the 31st minute the passage from solution to crystal was complete—a duration of 2 minutes. This is the shortest time the author has observed for this essentially slow process. The temperature at which the carbides began to crystallize out of solution was 708° C., and that is therefore the limiting temperature below which it would be impossible to retain the whole quantity of carbide in solution by any method of sudden cooling, a point which will be referred to again in Section (15).

(13) Spoiled Magnet Steel and its Restoration.

So far it has been assumed that in magnet steel all the constituent elements are playing the parts assigned to them in the magnetic mechanism; that the whole of the solvent iron is generating magnetism, and that the entire carbon content is usefully employed in the form of potency-giving molecules. But magnet steel as it comes from the steelworks falls a long way short of that ideal condition, the heat treatment which the steel receives in course of manufacture causing serious injury to the properties on which the power of a permanent magnet depends. It is not generally recognized how much harm is done. The injury is of two kinds, giving rise to a deficiency in the inherent magnetomotive force and a loss of potency. In effect, both the factors of magnetic energy suffer degradation.

Deficiency of magnetomotive force arises from the ultraheating of magnet steel. It is the lesser of the two evils, because the magnet maker who is aware of it can easily apply a complete remedy. Ultraheating will repay careful study by the metallurgist as well as the magnet maker, but to describe the tangled phenomena here would involve a long digression and the subject is therefore treated separately in an Appendix.

The loss of potency, which is due to the spoiling of magnet steel by decomposition, is a much more serious injury and there is no practicable remedy for it that can be applied after the steel has left the steelworks. This almost universal defect in magnet steel is the subject of the present section and it will be shown that the injury is preventible.

When starting on a journey through unknown country it is often helpful to be told where we are going. The author, having been compelled to spend four or five years investigating spoiled steel, has already made the journey and the outcome can be summed up in a few sentences. If the solute carbide molecules in magnet steel were stable chemical compounds, there would be no such thing as spoiled steel. Unfortunately,

the very molecules on which we rely for the creation of potency, suffer decomposition at temperatures to which magnet steel is exposed during manufacture. Decomposition of the carbide molecules breaks up the molecular pattern identified with potency, and hence magnet steel which has been exposed for some considerable time to any temperature within a certain danger zone loses much of its power to act as a permanent magnet. For the purpose of making magnets the steel is spoiled. Both tungsten magnet steel and cobalt magnet steel suffer degradation by spoiling, but the research now to be described was confined to tungsten steel.

Magnet makers are of course familiar with the fact that magnets made from the same batch of steel vary widely in their magnetic power, the difference between the best and the worst being much the same in every lot of steel. Without tracing this persistent lack of uniformity to its source, it was easy to attribute it to a number of causes, namely, the variable composition of the steel, the way it was rolled, the forging of the magnet, the temperature for hardening, the nature of the quenching bath, and the way the steel was immersed in it. All these would be suspected in turn, and from time to time modifications in practice would be introduced, more or less at random. But no matter what was done, excessive variation in magnetic power remained. It is to-day, as it ever was, the magnet maker's greatest trouble, and it has not been mastered because there was no obvious clue to the underlying cause.

The author found himself in possession of a clue by accident. Some years since, a Sheffield steel maker supplied a quantity of magnet steel nominally containing 0·7 per cent of carbon and 6 per cent of tungsten, proportions that should give a coercive force of about 69 in the hardened steel. The batch of steel consisted of a large number of lengths of rolled bar, and in the ordinary course two samples were cut off each length for testing purposes. The samples having been hardened and their coercive force measured, the values obtained were found to vary from about 46 in the best sample to 27 in the worst, the average of the whole lot being 36.

Deficiency of coercive force may arise, and frequently does arise, from deficiency of carbon. In the present case this cause was immediately suspected and a sample bar fairly representative of the whole lot was submitted to analysis. The steel was found to contain 0·69 per cent of carbon and 6·2 per cent of tungsten, a sufficiently close approximation to the specified composition. The coercive force corresponding with the composition ascertained by analysis should be 68, the observed average value being only 36.

This remarkable steel, then, contained carbon and tungsten in quantities which, if these elements were properly combined as solute molecules, should give a coercive force of nearly twice the observed value. The only possible explanation seemed to be that by some means or other the carbide molecules had been decomposed and that their constituent atoms, although still present in the steel as shown by the percentage analysis, were not in the condition that gives rise to potency and coercive force. In short, as a material for permanent magnets the steel was entirely spoiled.

The cause of the spoiling was not far to seek. On inquiring what had happened in the steelworks, it was ascertained that in order to soften the steel after rolling, the whole batch had been heated to about 900° C. and maintained at that temperature for a prolonged period (more than 24 hours), the steelmaker being apparently unaware that to soften tungsten magnet steel for easy machining it is only necessary to keep it at 700° C. for at most 10 minutes. It being evident that 900° C. is a dangerous temperature for tungsten steel, this clue formed the starting-point for an experimental investigation.

The first thing to be done was to verify the fact by subjecting some good magnet steel to prolonged heating at about 900° C. For this purpose three rolled bars were selected from a batch of tungsten magnet steel of standard composition, choosing bars which represented the characteristic variations in magnetic quality. Short lengths having been cut off each bar to serve as test-pieces, they were hardened and tested for coercive force. The values obtained were 76·0, 71·5 and 62·5.

TABLE 3.

Test-piece	Initial coercive force	Coercive force after heating at 900° C. for 7 hours	14 hours	21 hours
L31	76·0	55·0	43·5	36·5
L22	71·5	55·0	43·5	—
L49	62·5	51·0	43·5	38·5

Progressive decrease in the coercive force of hardened tungsten magnet steel, consequent on previous heating at 900° C.

The three test-pieces were next put into a furnace and heated to 900° C., and that temperature having been maintained for 7 hours the test-pieces were taken out of the furnace and allowed to cool down. Having removed the scale oxide formed during the prolonged heating, the test-pieces were hardened again and tested for coercive force. This cycle of operations was repeated twice more, so that by the end of the experiment the test-pieces had been subjected to a temperature of 900° C. for three periods of 7 hours each, or 21 hours altogether, with intermediate hardening and testing for coercive force. The result of the experiment is recorded in Table 3, showing the gradual spoiling of the steel that goes on at 900° C. After 7 hours at that temperature, tungsten steel is reduced to a condition in which it is little better than carbon steel as a material for permanent magnets, and at the end of 21 hours it is much inferior to carbon steel. The experimental data given in Table 3 have been used to construct the curve given in Fig. 13, which illustrates the gradual spoiling of tungsten magnet steel, of normal composition, at 900° C.

It is noticeable that although, to begin with, the

three test-pieces differed widely in coercive force, 14 hours at 900° C. reduced them all to the same level of inferiority. Why this should be was not understood at the time the experiment was made (June 1918), but a reference to the carbon-coercive-force curves now available for tungsten steel (Fig. 9) at once suggests a reason. Attention has already been drawn to the fact that carbon combines more readily with tungsten than with iron, and it is reasonable to suppose that when the conditions are favourable to decomposition, the carbide of iron will decompose more readily

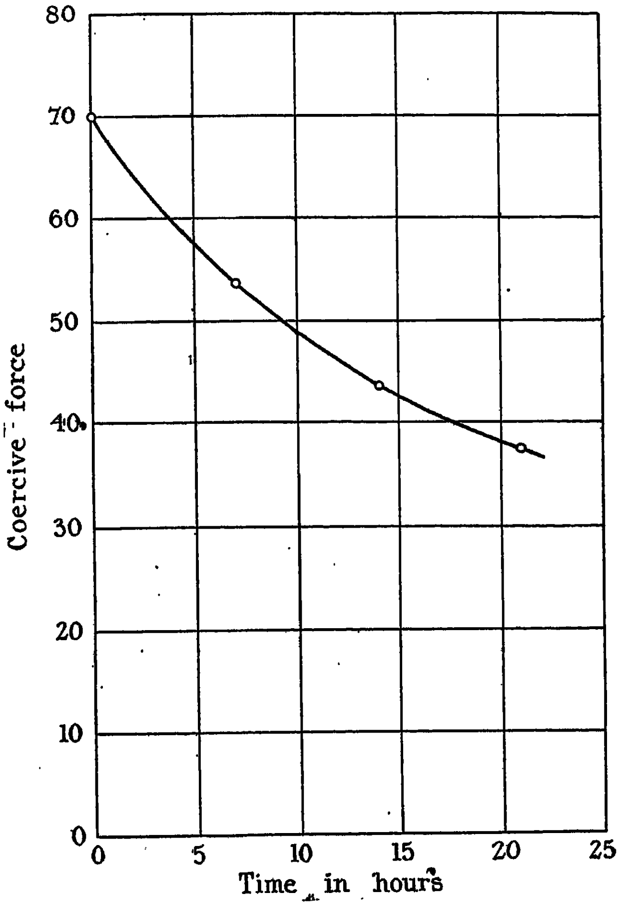

FIG. 13.—Spoiling of tungsten magnet steel. Curve showing the progressive degradation in the coercive force of the hardened steel consequent on previous heating at 900° C.

than the carbide of tungsten. Now the quantity of carbide of tungsten is determined by the quantity of tungsten and, since in this respect all three test-pieces are alike, the potency and coercive force arising from carbide of tungsten will be the same in all of them. Hence the initial differences in coercive force must be attributed to differences in the content of carbide of iron, and when the whole of that carbide has been decomposed, the remaining coercive force will be that due to carbide of tungsten: the carbon-coercive-force curve (Fig. 9) shows that under those conditions the coercive force cannot exceed 45, and it will be less than that amount if there has also been some decomposition of the carbide of tungsten. The experiment therefore indicates that at the end of 14 hours each test-piece had already arrived at this stage of equality in degradation; all the carbide of iron had already been decomposed.

Before going on with the investigation of spoiling, it will be convenient to describe a first attempt at the restoration of spoiled steel, made immediately after the conclusion of the experiment in spoiling recorded in Table 3. If we assume that spoiling is decomposition and that none of the dissociated elements escape at the surface of the steel, then it should evidently be possible to restore spoiled steel by re-melting it, because in that way the iron, the tungsten, and the carbon would, as it were, begin life all over again. But a little consideration suggested that restoration might take place at some temperature short of the melting point. It seemed probable that the high temperature to which high-speed tool steel is heated, in order to leave it hard on cooling down, might be intended incidentally to re-combine any solute carbide molecules that had suffered decomposition during the making of the steel, and in that case a similar high-heat treatment ought to restore magnet steel.

To put this idea to the test of experiment it was proposed to heat one of the three spoiled test-pieces to a temperature well above 1 200° C. for some minutes. The test-piece selected for the purpose was that made from the length L31 for which the initial coercive force was 76. It was anticipated that a good deal of carbon might have escaped from the surface of the steel in the course of the 21 hours' heating it had undergone, and to avoid a misleading result from this cause the surface of the test-piece was removed in the lathe to a depth of about 1·5 mm, leaving a cylindrical core for the experiment. This core was then heated in a bath of molten barium chloride to a temperature just over 1 300° C., at which point it was maintained for nearly half an hour*; it was then removed from the heating bath and allowed to cool down. After this treatment the core was hardened in the usual way by quenching from 850° C. The coercive force of the hardened core was then measured and found to be 71. This figure compares with 76 when in the initial state and 36·5 in the spoiled state. Although the potency of the restored cylindrical core, measured by coercive force, fell somewhat short of the initial value, the experiment was encouraging.

Here we may again interpret the result of an early experiment in the light of information which was not available at the time. Referring again to the carbon-coercive-force curve (Fig. 9), it will be found that the values 76 and 71 obtained for the coercive force in the initial and the restored states correspond with carbon contents of 0·81 per cent and 0·73 per cent respectively. Heating for 21 hours at 900° C., followed by about half an hour at 1 300° C., had therefore resulted in the abstraction of carbon from the entire section of the test-piece, the loss in the cylindrical core amounting to just 10 per cent of the quantity originally present in the steel.

* A couple of minutes at 1 300° C. would have been ample time for restoration; but this was not known at the time the experiment was made.

A steel test-piece which has been denuded of carbon to even a very small depth below the surface gives entirely spurious values for coercive force, the decarbonized layer acting as a magnetic shunt applied to the central core. For this reason, loss of carbon at the surface of the test-pieces added greatly to the difficulties encountered in a prolonged investigation of the spoiling effect. The one likely remedy, keeping the heated steel in a carbon-laden atmosphere, was deliberately put on one side, because there was no certainty that the steel would not take in carbon from its surroundings; and, if it did, there was no easy means of measuring the quantity so absorbed. In all the experiments adduced in this paper the effect of the inevitable loss of carbon has been eliminated either by removal of all the steel found to be denuded of carbon, or by analysis of the steel at the different stages of experiment. In a test-piece 2 or 3 cm^2 in sectional area,

TABLE 4.

	Portion of steel from bar JD257, and the heat treatment	Analysis		Coercive force
		Carbon	Tungsten	
1	The whole of test-piece E1 hardened in its initial state	0·726	6·02	71·0
2	The whole of test-piece E2 hardened after heating at 900° C. for 1·5 hours	0·605	5·98	50·8
3	The central core of test-piece E2 after the above treatment ..	0·736	5·93	60·5
4	The shell of test-piece E2 after the above heat treatment	0·480	6·03	—

Spoiling tungsten magnet steel. Results of experiments on a bar of rolled steel, spoiled by heating at 900° C. for 1·5 hours, showing that the central core is degraded by spoiling although it has lost no carbon.

loss of carbon in the central portion of the section only begins to be noticeable after spoiling at 900° C. has gone on for a good many hours. It was therefore an easy matter to avoid losing carbon in the central core of a test-piece by restricting the duration of spoiling to one or two hours, the degree of spoiling in even so short a period as an hour being easily measurable by the decrement of coercive force. A typical experiment of this kind is recorded in Table 4.

The figures given in the table were obtained from test-pieces made from a bar of steel of exceptional uniformity as regards carbon content and almost free from spoiling. The samples for the first analysis, giving the average composition of the whole sectional area of the bar in its initial state, were taken from positions contiguous to the ends of the piece of bar from which the two test-pieces were made. The test-pieces were cylinders 10 cm in length and 0·64 cm in diameter. Having measured the coercive force of the hardened test-pieces in the initial state, one of them was heated to 900° C. and maintained at that temperature for 1·5 hours. It was then put into the lathe, and the surface having been turned off to a depth of 1·08 mm, the central core in its spoiled state was hardened and tested for coercive force. This having been done, the content of carbon and tungsten in the central core was determined by analysis, the core being softened and turned into shavings for the purpose. It will be seen from the figures in Table 4 that although the spoiled central core happened to contain slightly more carbon than the average content of the original section, yet the coercive force had decreased by 10·5 units as the result of 1·5 hours' heating at 900° C.

Having demonstrated the fact that spoiling takes place when tungsten magnet steel is heated at 900° C., the next step was to ascertain how the rate of spoiling varies with the temperature. For this purpose a number of samples were cut from a bar of magnet

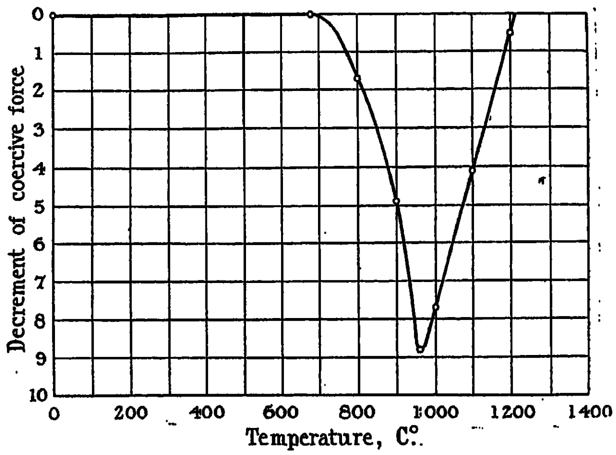

FIG. 14.—Spoiling of tungsten magnet steel. Curve showing the variation in degradation consequent on previous heating for 2·5 hours at different temperatures.

steel of about 3 cm^2 sectional area, and heated one at a time at different temperatures from 800° to 1 200° C., the time each particular temperature was maintained being 2·5 hours. After the heating, a cylindrical test-piece of small diameter was made from the central core of each sample, and hardened by quenching from 850° C. The coercive force of the hardened cylinders was then measured and the difference between the coercive force of the steel in its initial state and its spoiled state, that is to say the decrement due to spoiling, was plotted against the temperature of spoiling as a graph connecting temperature and rate of spoiling. The graph is reproduced in Fig. 14 and it is seen at once that spoiling goes on at the greatest rate at a temperature of 950° C.

Comparing the graph with the iron-carbon diagram given in Fig. 4, it is clear that the region of temperature within which spoiling occurs coincides with the region in which the iron in carbon steel, and presumably in tungsten steel also, is in the Gamma state. In Fig. 14 the exact course of the graph below 800° C. is a little

uncertain, but as a previous experiment had shown that magnet steel which had been maintained at 680° C. for 7 hours remained entirely unspoiled, the course of the curve cannot be far wrong. If any spoiling goes on below 750° C., that is to say when the iron is in the Beta state, it is evidently negligible in amount.

Above 1 000° C. the graph is a straight line, and when produced beyond 1 200° C. it cuts the line of zero spoiling at 1 214° C. There can hardly be a doubt that this is the point at which the allotropic change from Gamma to Delta iron takes place, and, assuming that to be so, the Gamma region is the danger zone of temperature for tungsten magnet steel, any temperature between 750° and 1 214° C. being a spoiling temperature.

The abrupt termination on the danger zone at 1 214° C. makes it natural to inquire what happens immediately above that temperature. The answer is to be found in an experiment made long before that to

TABLE 5.

Bar N4	Duration of heating (minutes)			Apparent coercive force	Increment	Mean increment
Test-piece	Heating up	At 1 240°	Above 1 214°			
1	0	0	0	45·5	—	—
4	0·67	0·25	0·42	53·2	7·7	7·85
10	0·67	0·25	0·42	53·5	8·0	
2	0·67	0·50	0·67	54·5	9·0	9·00
8	0·67	0·50	0·67	54·5	9·0	
5	0·67	1·0	1·16	55·5	10·0	10·25
11	0·67	1·0	1·16	56·0	10·5	
3	0·67	2·0	2·17	55·0	9·5	9·00
9	0·67	2·0	2·17	54·0	8·5	
6	0·67	4·0	4·17	53·0	7·5	8·00
12	0·67	4·0	4·17	54·0	8·5	

Attempt to restore spoiled tungsten magnet steel by heating at 1 240° C. The coercive force is that of the test-piece when hardened after the heat treatment.

which Fig. 14 relates. After making the first experiment in restoration, described above, an attempt was made to restore some of the magnet steel which had been completely spoiled by the steelmaker in the circumstances already mentioned. It will be remembered that the coercive force of this batch of steel varied from 27 in the worst bar to about 46 in the best. Before trying to restore the worst of the batch it was thought better to see what could be done with the best of it, and accordingly a bar which, in the hardened state, gave a coercive force of 45·5, was selected for trial. A dozen rods of small section having been cut from this bar, they were assembled in pairs and immersed in a bath of molten barium chloride, the temperature of which was maintained constant at 1 240° C., within a few degrees either way, during the experiment. The rods of steel attained the temperature of the bath in 40 seconds, as nearly as the time could be measured, and at pre-arranged intervals after that epoch the pairs of rods were withdrawn from the bath and allowed to cool down. All the rods were then hardened by quenching from 850° C., and tested for coercive force. The observational data obtained in this experiment are given in Table 5. In Fig. 15 a curve has been plotted from the data given in the table, showing a rapid initial rise in coercive force followed by a less rapid fall.

As a method for restoring spoiled steel to a condition in which it would be fit for making magnets the experiment was a failure. Estimated from its composition by analysis, the steel should give a coercive force of 68 when unspoiled, or completely restored, whereas the highest value attained, as the result of the heat treatment described, was only 56. Why the coercive force, after rising with great rapidity as the result of the first minute and a half in the heating bath,

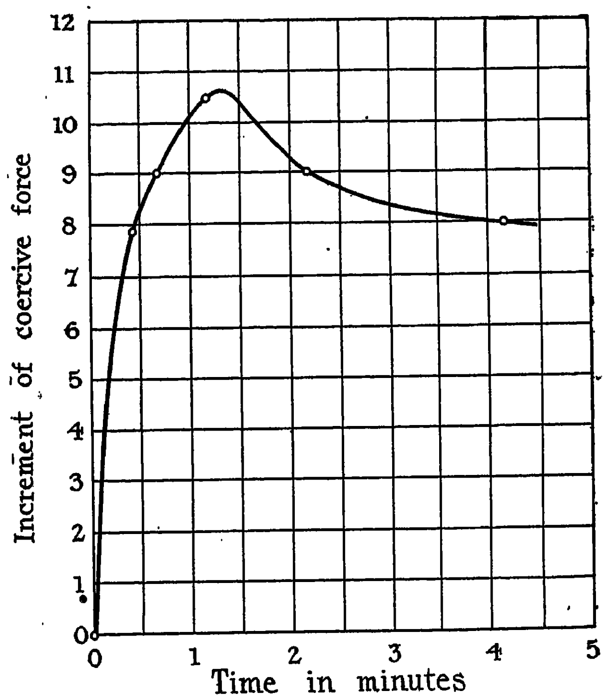

FIG. 15.—Curve showing the partial restoration of spoiled tungsten magnet steel by heating at 1 240°C.

should then begin to fall off, was not understood at the time. Long afterwards, when the effect of loss of carbon had been investigated, it was realized that in this experiment a decarbonized layer developed during the heating in the bath and rapidly increased in depth. Hence when the test-pieces came to be tested for coercive force each was in the condition of a bar magnet closely surrounded by a magnetic shunt of soft iron, the thickness of the iron and magnitude of the shunting effect depending on the duration of the heating. In these circumstances the values obtained for the coercive force became more and more erroneous as the decarbonized layer increased in thickness, and the only measurements on which reliance can be placed are those made on the test-pieces which had been withdrawn from the heating bath before the decarbonized

layer grew to an appreciable thickness. Interpreted in this way the falling off in coercive force seen in Fig. 15 indicates the steadily growing thickness of the decarbonized layer and the consequent increase in the shunting effect.

Knowing the cause of the falling off in the apparent coercive force (the spurious coercive force of a shunted magnet), we may disregard the erroneous figures and concentrate our attention on what took place before the loss of carbon began to have an appreciable effect. The first pair of test-pieces to be removed from the heating bath had been at a temperature of 1 240° C. for 15 seconds. But assuming that restoration actually began as soon as the temperature rose above 1 214° C. (the point at which the spoiling effect ceases) an addition of from 10 to 15 seconds must be made for the time occupied by the steel in rising from 1 214° to 1 240° C., making at the most a period of 30 seconds at a temperature above 1 214° C. Within that time the condition of the steel was restored to an extent which, when the test-pieces were subsequently hardened, gave an increase of 7·85 units in the coercive force. From this it appears that before carbon escaped in appreciable quantity, restoration was going on at a rate corresponding with an increase of more than 15 units of coercive force in a minute.

Now the initial coercive force of the steel in the spoiled state having been 45·5, and the value for unspoiled steel of the composition given by analysis being 68·0, the number of units of coercive force to be added for complete restoration would be 21·5, and hence at the rate of restoration of 15 units a minute the restoring process would be completed in less than 2 minutes, provided the rate were maintained to the end and that the escape of carbon could be prevented.

Comparing this experiment with the one recorded in Fig. 14, we find that at 950° C. spoiling is proceeding at the maximum rate, the coercive force decreasing by roughly 9 units in 2·5 hours, a rate of 3·6 units per hour. At 1 200° C. spoiling is still going on, although with extreme slowness, the coercive force falling less than a unit in 2·5 hours, a rate considerably under 0·4 units per hour.

On passing the boundary temperature, which Fig. 14 places at 1 214° C., a sudden and astonishing change takes place, and at 1 240° C., only 26 degrees above the boundary, restoration is found to be going on at the rate of 15 units of coercive force *a minute*. This is equivalent to a rate of 900 units per hour and is to be compared with a maximum rate of spoiling which, as we have just seen, was only 3·6 units per hour. In other words, restoration above the boundary temperature is 250 times as quick as the spoiling below the boundary.

Assuming the boundary temperature, 1 214° C., is that between Gamma and Delta iron, and that spoiling and restoring result from decomposition and recombination of the solute molecules WC and Fe_3C, this great disparity in the rates of spoiling and restoring is a clear indication of some fundamental difference in the chemical reactions of Gamma and Delta iron on the solute carbides. We have already seen in Section (7) that if sudden changes in specific heat are equivalent to changes in atomic weight, Gamma and Delta differ from each other much as one element differs from another, and it is therefore by no means surprising that they should be found to possess very different chemical properties.*

Two more experiments may be referred to. After investigating the effect arising from loss of carbon, a number of samples, taken from one of the least badly spoiled bars in the batch of steel which had been "softened" by the over-zealous steel maker, were heated to a restoring temperature for different periods of time, and the central cores remaining after the removal of the decarbonized layer were hardened and tested for coercive force. The values obtained are given in Table 6. The spurious values of coercive

TABLE 6.

Bar N1 Test-piece	Duration at a temperature above 1 250 °C.	Coercive force of the hardened test-piece: Whole section of test-piece	Coercive force of the hardened test-piece: Central core of test-piece	Coercive force (average)
D3	No treatment; hardened in the initial spoiled state	51·6	—	51·2
F1		50·4	—	
H2		51·7	—	
	Minutes			
B3	1·0	—	68·0	67·8
F2	4·5	55·7	65·0	
D2	7·0	51·9	63·7	
G3	7·5	51·5	72·0	
B1	14·0	48·9	64·5	
F3	14·0	46·6	68·0	
H3	14·5	47·3	73·5	
D1	15·0	47·7	72·5	
G1	25·0	43·9	62·5	
J1	65·0	58·0	68·7	

Experiments showing the complete restoration of the central core of test-pieces made of badly spoiled tungsten magnet steel. For steel of the composition found by analysis, and in the unspoiled state, the estimated coercive force is 67·0.

force obtained from the whole section of the test-piece, before removing the decarbonized layer, are included in the table to show how utterly misleading they are. The mean value of the coercive force of the central cores, namely 67·8, should be compared with that corresponding to the carbon content of the steel, which analysis showed to be 0·691 per cent; making use of the carbon-coercive-force curve (Fig. 9) to translate carbon content into coercive force. It will be found, on making the comparison, that the condition of the steel in the central cores was fully equal to that of unspoiled tungsten magnet steel.

The last experiment to be noticed is recorded in

* The low-temperature chemist cannot tackle red-hot substances like Gamma iron and Delta iron. But what the chemist cannot do magnetism has accomplished, affording, perhaps for the first time, a clue to the chemical attributes of the allotropic varieties of iron.

Fig. 16 in the form of three demagnetization curves: one obtained from a specimen of tungsten magnet steel selected from a large number of bars as being in an almost unspoiled state; the second from the same sample after spoiling at a temperature of 942° C. for 13·1 hours, and the third from the same sample bar after restoration at 1 300° C. In the course of the prolonged period of spoiling at 942° C. the steel lost carbon throughout the entire sectional area, analysis showing that the carbon content of the central area, which was initially 0·736 per cent, had decreased to 0·708 per cent as the result of the prolonged heating. Reference to the carbon-coercive-force curve shows that in unspoiled steel a carbon content of 0·708 would give a coercive force of 69·0. The actual coercive force of the steel containing that percentage of carbon

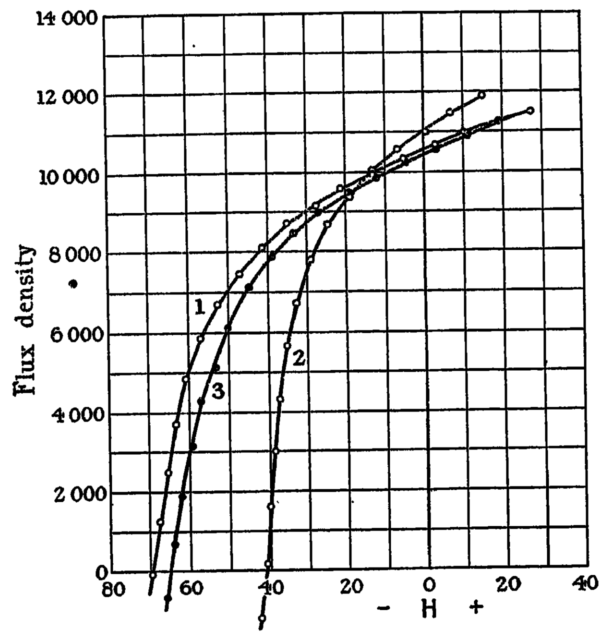

FIG. 16.—Demagnetization curves obtained from hardened tungsten magnet steel in different molecular states:—

(1) As received from the steelworks.
(2) After being spoiled by heating at 942° C. for 13 hours.
(3) After being restored by heating at 1 300° C.

(after spoiling for 13·1 hours at 942° C.) was only 41·5, a degradation of 28 units.

The piece of steel taken from the same sample for the purpose of restoration was first spoiled along with the specimen last referred to. That is to say it was spoiled for 13·1 hours at 942° C. Having been spoiled it was raised to a temperature of 1 300° C. and maintained at that point for 21 minutes, a duration much in excess of what was needed. During this time a good deal of carbon diffused from the central portion of the large sectional area into the outer portion which had been greatly denuded of carbon during the spoiling. The result of this transference of carbon is seen in the low carbon content of the central core, namely, 0·669 per cent. Unspoiled steel containing that amount of carbon has a coercive force of 65·7, which compares with the observed value 64·9 for the restored specimen. There was reason to suspect that, in heating the test-piece preparatory to hardening it, insufficient time had been given for the complete solution of all the carbide in the solvent iron. The test-piece was therefore hardened a second time, taking care to give ample time for the carbide to dissolve. When tested after the second hardening, the steel was found to have a coercive force of 66·4, which is slightly greater than the computed value, given above, for steel containing 0·669 per cent of carbon. Complete restoration was, therefore, finally effected in this case, in the sense that the whole of the carbon remaining in the steel after the spoiling was recombined as solute carbide molecules.

In the foregoing account of the phenomena of spoiling, frequent reference has been made to unspoiled magnet steel. Strictly speaking, however, an absolutely unspoiled condition at room temperature is unattainable, since a piece of steel which has been perfectly restored at a temperature within the Delta region necessarily passes through the danger zone on cooling down, and during that passage some degree of spoiling is inevitable. But under the conditions of cooling that ordinarily occur in practice the steel is only within the danger zone for a brief period of time and the resulting loss of coercive force is negligibly small. As a rather extreme example, we may suppose that as much as three hours is occupied in cooling the steel from 1 220° to 100° C. Now the time occupied in traversing the Gamma region, or danger zone, from 1 220° to 750° C., is always about one-twelfth of the whole time occupied in cooling down to 100° C., and hence at the given rate of cooling the danger zone would be traversed in about 15 minutes. But the extent of spoiling within 15 minutes would decrease the coercive force of the subsequently hardened steel by no more than half a unit in a total of 70, and in practice, steel which has only suffered spoiling to that extent may fairly be described as unspoiled.

The investigation of the spoiling and restoring of tungsten magnet steel involved, in all, more than four years of almost continuous experimental work. Nature did nothing to assist the experimenter. The confusing facts presented themselves in no sort of logical sequence, and the significance of many of them was not grasped until the time arrived to review the research as a whole. Looking back, it is easy to perceive that the four experiments recorded in Figs. 13, 14, 15 and 16, contain in themselves the gist of the whole matter.

Although the experiments described in this section demonstrate the fact that spoiled tungsten magnet steel can be restored, the problem that faces the magnet maker remains unsolved. He receives from the steel maker a batch of rolled steel the bulk of which is more or less spoiled, and usually about a quarter of it will be very badly spoiled. But the steel is not only spoiled. It has also lost carbon, the superficial layer of each spoiled bar being more or less denuded of carbon. Now to bring the spoiled bars into a condition fit for making magnets it is not enough to restore the steel as it stands. It is essential to secure uniformity of carbon content throughout the sectional area, and to do that the deficiency of carbon in the superficial layer must be made good by adding carbon, and adding it in just the right quantity. By no means an easy problem to solve,

yet it is not impossible that a convenient process might be discovered by research.

However that may be, the true remedy for spoiled magnet steel is prevention, and that rests with the steel maker. It should not be difficult to avoid the production of spoiled magnet steel, and in practice the steel maker already makes a few bars of unspoiled steel now and again, by accident. He has only to do it on purpose and the problem will be solved.

(14) Spoiled Steel: Chemical and Magnetic Analysis Compared.

When the degradation of spoiled tungsten magnet steel has been determined in terms of coercive force, the carbon-coercive-force curve (Fig. 9) enables the loss of coercive force to be translated into the quantities of the two carbides which have been decomposed under given conditions of time and temperature. Deducting these amounts from the quantities initially present in the steel, as determined from a percentage analysis, the remainder values give the molecular composition of the spoiled steel. To justify the assumption that spoiling is decomposition, it would, of course, be necessary to ascertain the molecular composition of the spoiled steel by the elaborate process of separating and recovering the carbides as residues, and then determining their molecular composition by chemical analysis.

The researches of Arnold and Read leave little room for doubt that in tungsten magnet steel, in the softened state, the carbon is present in the form of the two carbides WC and Fe_3C, and if there is still any doubt about the presence of those two carbides when the steel is in the hardened state such a comparison as that described in the last paragraph should settle the question one way or the other.

By a fortunate chance the necessary chemical data for a comparison of that kind are already available, having been obtained incidentally by Professors Arnold and Read in the course of their work on the carbide residues of tungsten steels. On turning to the technical details of their method of research* it appears that, as a preliminary, each specimen of steel to be examined was first heated to 950° C. and maintained at that temperature for a period of about 6 hours. We are not concerned with the object of this procedure. It is enough to know that each specimen received this preliminary thermal treatment, and that by so doing the steel was partially spoiled. Moreover, the temperature chosen, 950° C., happens to have been that at which spoiling goes on at the greatest rate (Fig. 14). It was, therefore, from specimens of steel degraded to that particular degree that the carbide residues were obtained; and consequently the molecular compositions deduced from the analysis are those of tungsten steel which had been spoiled for 6 hours at 950° C.

With these accurate chemical determinations at hand, it was possible to make the comparison between the chemical and the magnetic methods of ascertaining the molecular composition of spoiled tungsten magnet steel. Among the tungsten steels examined by Arnold and Read was one † which had almost exactly the percentage composition of the best tungsten magnet steel, analysis showing that it contained 0·71 per cent of carbon and 5·37 per cent of tungsten. This sample was therefore chosen by the present writer for the computation of the molecular composition from magnetic data. The arithmetical work occupies too much space to be given here and it must suffice just to indicate the method. To begin with, the degradation in 6 hours at 900° C. was ascertained from the curve in Fig. 13. Next, the ratio of the degradation at 950° C. to that at 900° C. was determined by means of the graph in Fig. 14; and the final step was to compute the quantity of carbide of tungsten decomposed in 6 hours at 950° C. from the value of the coercive force determined for spoiled steel by the demagnetization curves given in Fig. 16. Throughout these calculations the carbon-coercive-force curve given in Fig. 9 was used for translating differences in coercive force into percentages and quantities of carbon and carbides.

* Arnold and Read: *Proceedings of the Institution of Mechanical Engineers*, 1914, p. 223.

† Arnold and Read, loc. cit., sample No. 1246.

Table 7.

Condition of the steel and method of determination	Number of molecules per 100 atoms of carbon		
	WC	Fe_3C	C
1. The steel unspoiled ..	54	46	0
2. The steel spoiled by heating at 950° C. for 6 hours:— Composition:— (a) By chemical analysis of residue left after removing the solvent iron by electrolysis (Arnold and Read)	46	24	30
(b) By the estimated coercive force of the hardened steel (author)	49	23	28

Molecular composition of badly spoiled tungsten magnet steel. Percentage composition of the steel: Carbon 0·71 per cent, tungsten 5·37 per cent.

The comparative figures for the molecular composition of the spoiled steel, deduced from the chemical and from the magnetic data, are given in Table 7, where the molecular composition is stated in each case for quantities containing a total of 100 atoms of carbon. The first line gives the composition of the carbon compounds when the steel is unspoiled, based on the percentage analysis given by Arnold and Read. The figures in the second line are taken from their analysis of the carbide residue obtained from the spoiled and softened steel. The third line gives the result of the present writer's computation, based on the coercive force of hardened tungsten steel of the given percentage composition.

The figures given in Table 7 may be left to speak for themselves. Whether the problem of spoiled tungsten magnet steel is investigated by the chemical analysis of residues obtained from the steel in the softened state, or by the magnetic phenomena of hardened steel, the

answer is the same: spoiled steel is decomposed steel. At any temperature between 800° and 1 200° C., to state the limits in round numbers, the carbide molecules on which the potency of magnet steel depends, suffer gradual decomposition, marked by a corresponding decrease in the coercive of the steel when it is subsequently hardened. To restore the potency, the broken-up molecules must be put together again, a recombination which quickly takes place when the temperature of the steel is raised a few degrees above the boundary where the solvent iron changes from Gamma into Delta iron. But the full potency can only be regained provided the dissociated elements remain inside the steel. In steel of large sectional area such as the ingot or billet of the steelworks, this condition would be reasonably well fulfilled; but in pieces of steel of the size of permanent magnets some of the carbon always manages to escape and complete restoration is then impracticable.

(15) Hardening, Softening and the Surplus Solute.

Alpha iron provides the mechanism that generates the magnetic flux in a permanent magnet, but the other factor, the potency, is of the feeblest in soft iron. The very small coercive force of pure soft iron, rather less than 2 units, indicates an almost perfect uniformity in the distribution of the magnetic molecules, and if iron is to serve any useful purpose as a permanent magnet, the potency of the magnetic mechanism must be very greatly increased by importing variformity.

One obvious way of bringing about a variformity of distribution is to squeeze the iron by rolling or hammering or wire drawing, and it is well known that by any of these ways of distorting the crystalline structure, it is possible to increase the trifling coercive force of iron by several units. Incidentally, the hardness is also increased a little. But apparently the increase in potency and hardness arises from a bodily shifting of whole crystal groups rather than any modification in the crystal elements themselves, and to obtain any large effect, to endow the iron with the potency required in a permanent magnet, something more subtile than mechanical distortion is needed. Something must be done to modify the molecular pattern in a regular fashion throughout the crystalline mass of iron, so as to produce a systematic variformity in the distribution of the magnetic molecules. That something consists in dissolving certain compounds of carbon in the iron; and what mechanical squeezing does feebly and in a somewhat irregular way, a number of solute carbide molecules will do with far greater effect. Where a steam hammer manages to add two or three units to the coercive force, the solution of a fractional percentage of carbon will increase it by 50 units, or 70 or even 200 units according to the nature of the carbon compounds employed as potency-giving solute molecules.

Where the carbide molecules find their place in the magnetic mechanism, how they act on the molecules of iron, and why they only have the desired effect when they are in solution, is not known, or but vaguely surmised. But wherever they are, they certainly act individually and systematically throughout the mass of solvent iron which serves as the magnetic mechanism, doing by atomic force what the hammer or the rolling-mill can never do. By their presence carbide molecules convert iron into steel, and when they are in solution they create the potency which renders the steel fit for a permanent magnet.

To make a powerful magnet, the magnetic mechanism must combine great potency with a high degree of inherent magnetomotive force, and both factors must be taken into account in determining the best proportion of potency-giving carbon compounds in magnet steel. It is found by experiment that a permanent magnet maintains the maximum amount of useful magnetic energy when the steel contains about 0·72 per cent of carbon in the form of soluble carbides, the whole amount being in solution. It is, of course, essential that the iron in the steel should be in the magnetic state, and since Alpha iron only dissolves about 0·24 per cent of carbon (one-third of the whole carbon content) as a solution in stable equilibrium, the problem is how to induce the remainder of the carbon, two-thirds of the whole, to enter into solution.

It was mentioned at the outset of Section (8) that complete solution of the whole of the carbon in magnet steel is effected by the ordinary process of hardening. Like a good many other things discovered or invented by primitive man, the hardening operation is of the simplest character. The temperature of the steel having been raised to a bright red heat, the metal is suddenly cooled by plunging it into cold water. Here again we have an example of formidable difficulties masked by an outward simplicity. It is very much easier to perform the hardening operation than it is to explain it. Nevertheless, an explanation will be attempted here in order to help the reader in forming some idea of the peculiar condition of hardened magnet steel.

What the hardening process effects is the solution of the whole of the carbon, notwithstanding the fact that the solvent iron is in the Alpha state, and since the amount of carbon in magnet steel is about three times as much as Alpha iron naturally dissolves, it seems impossible to believe that the molecular condition in the hardened steel is one of equilibrium. Let us imagine the state of things when a solute molecule has been put into the position it must occupy among the molecules of Alpha iron, as a constituent part of a solution which is not in equilibrium. If the molecule is free to move it will certainly not remain in the solution position, and until someone discovers how to bring about equilibrium under the assumed conditions, the only way to prevent the molecule from moving away is to deprive it of the power to move. Hence to endow the steel with the potency required in a permanent magnet needs two operations. First, the whole quantity of carbide in the steel must be dissolved by some means or other, and then while the carbide molecules are still in their solution positions, they must be deprived of their mobility. In this way the whole of the carbon present in magnet steel can be made to play its part in creating the potency-giving molecular pattern. It is the pattern of solution and serves the intended purpose —so long as it lasts—but it can hardly be a condition of equilibrium.

Taking the two parts of the hardening process in turn,

the first is the dissolving of the whole of the carbon. Now any of the allotropic varieties of iron, other than Alpha iron, will readily dissolve a good deal more carbon than 0·72 per cent. The first step therefore must be to transform the solvent iron into Beta, or Gamma, or Delta, by heating the steel to the appropriate temperature. But although any of these varieties of iron will dissolve all the carbon, no one of them does so better than the others, and hence there is nothing to be gained by raising the temperature much beyond the point at which the whole of the iron assumes the Beta form. In tungsten magnet steel the conversion of Alpha into Beta iron is completed at a temperature of 790° C., and for cobalt steel the corresponding temperature is 870° C. Allowing a small margin, the temperature to which the steel should be raised for the purpose of dissolving the carbide might be 820° and 900° C. respectively. Within three or four minutes after attaining the necessary temperature, which must be well within the Beta region, the whole of the carbon will have dissolved and the first operation is over.

Complete solution has now been accomplished, but only by converting the solvent iron into one of the non-magnetic varieties. The next thing to be done is to re-convert the iron into the magnetic or Alpha state by lowering the temperature, and at the same time prevent the carbide molecules from passing out of solution when the iron assumes the Alpha form. That is to say the solute molecules must be deprived of their mobility before they have had time to move from their solution positions. But at the high temperature where the change from Beta to Alpha occurs, the molecular mobility is so considerable that the whole of the surplus quantity of carbon, about two-thirds of the whole amount in the steel, would pass out of solution within a couple of minutes after the allotropic change had taken place. Hence the necessity for robbing the carbide molecules of their mobility in the shortest possible time. Now there is only one way to deprive molecules of mobility, and that is to lower the temperature of the steel to a point at which mobility, if not entirely suppressed, is at all events negligibly small. Probably the last trace of mobility only vanishes at the absolute zero of temperature, but fortunately for the toolmaker and the magnet maker molecular mobility decreases with such extreme rapidity as the temperature falls below a red heat that by the time a piece of steel has cooled down to room temperature the solute molecules have almost entirely lost their freedom.

The second operation therefore consists in lowering the temperature of the steel as quickly as possible from some point at which the whole of the carbon is in solution, down to room temperature. As the temperature falls below the region where the change from Beta to Alpha takes place, the solute carbide molecules lose their equilibrium as constituent parts of a stable solution; but before they have time to move the steel is cold and the mobility gone. Robbed of the power to move there is nothing for the carbide molecules to do but stop where they are, in the positions characteristic of the state of solution, and consequently the molecular pattern that gives potency is completely preserved in the steel. Briefly, the steel is first heated to bring about the pattern of solution and then by the more or less sudden cooling to a low temperature the carbide molecules are, so to speak, frozen in their solution positions, thus preserving the pattern that gives the steel both hardness and potency.

From time immemorial the primitive workman has been hardening steel by the method of sudden cooling, successfully performing the operation without giving a thought to the sequence of events on which success depends. It is only natural to suppose that steel which has been hardened by quenching will retain its hardness for ever. Very likely it would if the solute molecules which give the hardness were absolutely unable to move, but in fact they still have a modicum of freedom at ordinary room temperatures; a mobility so slight that it has hitherto received little attention if it has not escaped notice altogether. But slow changes in the structure of hardened steel, arising from molecular mobility, are easily detected by magnetic means and in Section (16) evidence will be given of the gradual decay of potency in steel which has been hardened by rapid cooling.

In course of time, then, hardened steel may very slowly decay, but while we are actually engaged in hardening a piece of steel it is the immediate effect that matters, and so far as that goes the molecular mobility at any temperature from 100° C. downwards is so exceedingly small that it may be dismissed as negligible. In short, when the temperature has fallen to 100° C. the steel is as good as cold so far as the hardening process is concerned. Again using the analogy of freezing, a temperature of 100° C. may be regarded as the freezing point of the operation of hardening, a conventional point below which the little mobility that remains may safely be ignored for the time being.

In the foregoing explanation of the process of hardening by quenching, the cooling of the steel has been described as taking place very quickly if not suddenly, no particular rate of cooling being implied. We must now turn our attention to the effect which the rate of cooling has on the degree of potency and hardness. If the steel is cooled slowly, the whole of the surplus carbide has time to pass from solution to crystal long before the steel is cold and the mobility gone. But if the rate of cooling is gradually increased, sooner or later a critical speed will be attained which gives only just enough time for the whole quantity of surplus carbide to pass out of solution before the temperature falls to the conventional 100° C., the point of zero mobility for our present purpose. At the critical rate of cooling complete softening ends and hardening begins, for at any greater speed there will not be enough time for all the surplus carbide to pass out of solution, and since some fraction of it will remain in solution the steel will have acquired a corresponding increment of hardness and potency.

Although carbon passes out of solution because Alpha iron, under normal conditions of equilibrium, cannot dissolve the whole amount of carbide present in magnet steel, the passage from solution to crystal does not begin with the first appearance of Alpha iron. It has already been noticed that with 0·72 per cent of carbon dissolved in Beta iron the solution is not saturated,

and it is clear that any carbide molecules, released from solution when the first portions of Beta iron are undergoing conversion into Alpha, will easily dissolve in neighbouring unsaturated solution. This transference of solute carbide molecules from what was Beta but has become Alpha, to the solvent iron which is still Beta, will go on until the remaining Beta iron can dissolve no more, having become a saturated solution. From this point onwards the solute carbide molecules, rejected from solution in consequence of the continued allotropic transformation from Beta to Alpha iron, are debarred from taking refuge in the remaining Beta and their only alternative is to assemble themselves in the crystalline form, intermingled with crystals of Alpha iron. Hence it is found that when a piece of magnet steel is slowly cooling down, the presence of Alpha iron begins to be indicated by the appearance of magnetism some little time before there is any sign of carbon passing out of solution. But a little later the saturation point is reached and the Beta iron can dissolve no more carbon. At that moment the carbon compounds begin to pass out of solution with a very noticeable release of energy in the form of heat. All this is well seen in Fig. 12 (page 748), where the curves indicating the magnetic change and the release of energy relate to a sample of 6 per cent tungsten magnet steel containing 0·65 per cent of carbon. As nearly as it is possible to judge from the overlapping waves, the saturation point occurred at the 29th minute of the experiment, the temperature of the steel being 708° C. at that moment. The first sign of magnetism, and therefore of Alpha iron, had made its appearance a minute and a half earlier when the temperature was 750° C. At the end of the 31st minute the whole of the surplus carbide had passed out of solution, the transfer from solution to crystal having occupied just two minutes, during which time the temperature fell from 708° to 652° C., a drop of 56 degrees. The rate of cooling at this stage was therefore 28 degrees a minute, and obviously this speed must be greatly exceeded if any of the surplus carbide is to be retained in solution in order to achieve a hardening effect.

To ascertain the effect of a considerable increase in the rate of cooling, let us imagine the same experiment to be performed at twice the speed, so that just below the saturation point the temperature will be falling at the rate of 56 degrees a minute. For a first approximation we may suppose that the transfer of the surplus carbon from solution to crystal occupies the same time as before, namely, 2 minutes, since the rate of transfer depends only on the mobility and the mobility on the temperature. But in 2 minutes at 56 degrees a minute the temperature will fall 112 degrees, and hence the transfer of carbide will now end at 708 — 112 degrees, which is 596° C. That is to say, when the rate of cooling is doubled, the temperature at which the passage of the surplus carbon out of solution comes to an end will be 56 degrees lower down the temperature scale. This example makes it clear that although surplus carbide must always begin to pass out of solution at the saturation point, the process will spread down the temperature scale as the rate of cooling is increased. Moreover, since the point at which the transfer of the surplus quantity comes to an end will be carried further and further down the scale, the mean temperature at which the passage of carbide takes place will be progressively lowered and with it the mobility. Hence, as the speed of cooling is steadily increased the point that marks the end of the transfer of surplus carbide from solution to crystal will fall down the temperature scale at a growing rate.

An illustration of the way in which the transfer of the surplus carbon gradually spreads from the saturation point down the scale of temperature is given in Fig. 17, where the graph expresses the relation between the

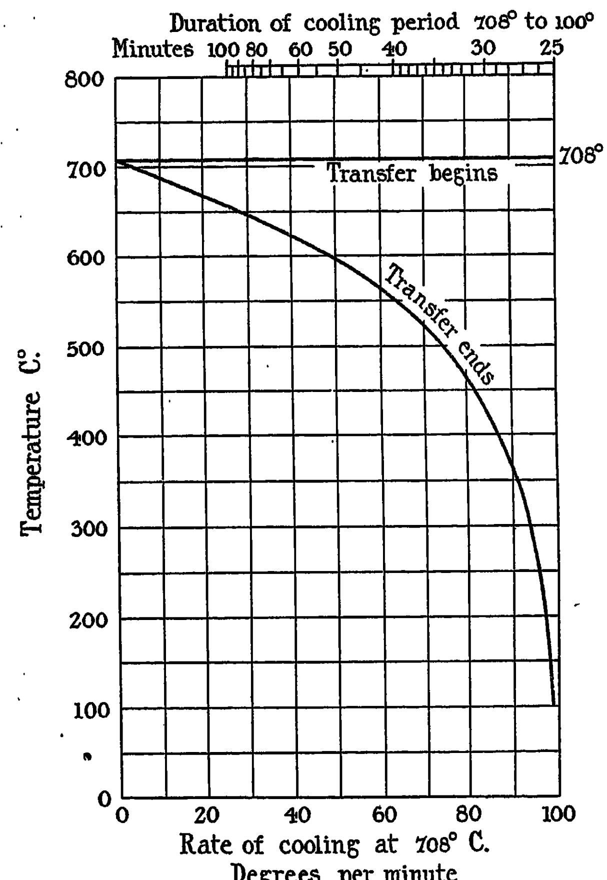

FIG. 17.—The softening of tungsten magnet steel. Curve showing how the range of temperature within which the surplus carbide passes out of solution, increases gradually as the speed of cooling is increased. (Computed by the author.)

speed of cooling and the point on the temperature scale where the transfer comes to an end. The same data have been used in constructing the graph shown in Fig. 18, where *the time* occupied by the passage of the surplus carbon from solution to crystal is plotted against the speed of cooling. These two diagrams relate to tungsten magnet steel with a carbon content of 0·72 per cent and tungsten 5·5 per cent. Two-thirds of the carbon, 0·48 per cent, is assumed to be the surplus which is insoluble in Alpha iron under normal conditions of equilibrium. The forms assumed by graphs of the kind shown in Figs. 17 and 18 depend both on the shape of

the cooling curve and on the law connecting the rate of transfer of carbon with the temperature. In the present example the diagrams are based on a cooling curve of the ordinary pseudo-logarithmic shape obtained experimentally from a bar of steel cooling in the open air of a room. Horizontal ordinates in both Fig. 17 and Fig. 18 give the rate of cooling at a temperature immediately below the saturation point. An inverse scale has been added in order to show the time occupied in cooling from 708° down to 100° C.

Observational data from which to determine the law connecting rate of transfer of carbon with temperature are very few and far between, and for this reason the two diagrams have no great claim to attention on the score of numerical accuracy. Nevertheless, they show in a general way how things go; how the rate of

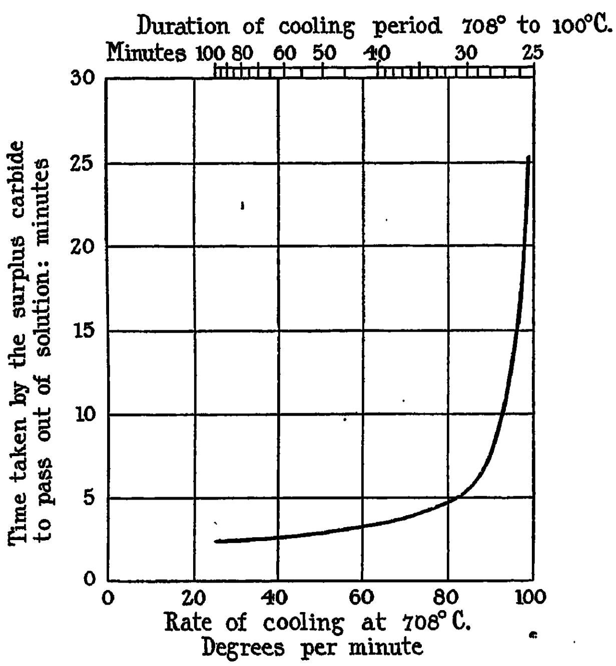

FIG. 18.—Softening of tungsten magnet steel. Curve showing how the time taken by the surplus carbide to pass out of solution gradually increases as the speed of cooling is increased. (Computed by the author.)

cooling governs the passage of the surplus carbide from solution to crystal at cooling speeds below the critical value where complete softening ends and hardening begins. In short, Figs 17 and 18 embody the cooling conditions which leave the steel in the completely softened state. The object of softening magnet steel is to enable it to be machined with ease, and that object is attained as soon as the whole of the surplus carbide has passed out of solution. Whether the passage of the carbide occupies 2 minutes or 2 hours is immaterial. Again, after the passage of the whole of the surplus carbide from solution to crystal has been accomplished, it is quite immaterial how slowly or how quickly the steel cools. As an example, let the initial rate of cooling be about 30 degrees C. a minute. We see from Fig. 17 that at this cooling speed the transfer of the whole of the surplus carbide in magnet steel will have come to an end, and the softened state will have been created by the time the temperature of the steel has fallen to 650° C. At this point, although the steel is still red hot, it may be suddenly cooled by plunging it into cold water without in any way affecting the softness, complete softening having taken place before the quenching began. True, the cooling robs the carbide molecules of their mobility, but to deprive them of mobility when they have already passed from solution to crystal is equivalent to locking the stable door after the steed is stolen. It is more than likely that this unusual instance of rapid cooling will leave some readers of this paper unconvinced, so deep-rooted is the notion that quenching red-hot steel in cold water must necessarily make it harder. Another idea, equally deep-rooted, is that steel is best softened by exceedingly slow cooling; yet it is easy by a few simple experiments to demonstrate the fact that all rates of cooling not exceeding the critical rate are equally effective in bringing about the completely softened state in steel. The curve given in Fig. 17 presents the same fact in another way and, by linking it with the passing of the surplus carbide out of solution, gives it a rational explanation.

We now pass to the consideration of rates of cooling in excess of the critical speed which marks the end of complete softening and beginning of hardening. When the cooling from the saturation point downwards goes on so quickly that the temperature has fallen to 100° C. before the whole of the surplus carbide has passed out of solution, the steel acquires additional potency and hardness commensurate with the amount of surplus carbide which is retained in solution.

In what follows, it will be convenient to refer to the region of temperature extending from the saturation point down to 100° C. as the *mobile region*, since it is the region within which the carbide molecules are impelled to pass out of solution and have the requisite mobility to do so. Looking at Fig. 18, we see that when the temperature of the steel was falling at such a rate that the time occupied in traversing the mobile region was about 25 minutes, there was just enough time for the whole of the surplus carbide to pass out of solution. The magnet steel to which Fig. 18 relates contained 0·72 gramme of carbon per 100 grammes of steel, of which about 0·24 gramme would be retained in solution under normal conditions, when the solvent iron was converted into the Alpha state. The remainder of the carbon, about 0·48 gramme, would constitute the surplus. Hence a duration of 25 minutes within the mobile region just gives enough time for 0·48 gramme of carbon to pass out of solution. Now, without in any way changing the shape of the cooling curve, let the cooling speed be doubled. The duration within the mobile region will be halved and consequently there will only be enough time for half the surplus carbon to pass from solution to crystal and the other half, 0·24 gramme will be retained in solution, notwithstanding the allotropic change of the solvent iron from Beta to Alpha. When the steel is cold, the amount of carbon in solution will now be the quantity which is normally soluble in Alpha, namely 0·24 gramme, plus the 0·24 gramme which has remained in solution, or at all events quasi solution, for want of time to pass from solution

to crystal. The steel will therefore contain twice as much carbon in solution as it would retain under normal conditions of equilibrium; and with twice the quantity of carbon in solution the potency and hardness will be largely increased.

But by quenching a piece of steel in water it can be cooled through the mobile region in very much less time than half 25 minutes. For example, a magnet weighing a couple of pounds, quite a large size for a permanent magnet, can be quenched in about 15 seconds. This is just 1/100th part of 25 minutes, and consequently if the steel cools through the mobile region in 15 seconds there will only be enough time for 1/100th part of the surplus carbon to pass out of solution. That is to say, 0·0048 gramme of carbon will pass out of solution and the remainder of the surplus, namely, 0·475 gramme, will be compelled to remain in solution. Adding this quantity to the 0·240 gramme, which is normally soluble in Alpha iron, the steel when cold will contain 0·715 gramme of carbon in solution, out of a total carbon content of 0·720 gramme per 100 grammes of steel. These figures show that by rapid cooling in water rather more than 99 per cent of the entire carbon content of magnet steel can be retained in solution, even in the case of a large magnet.

The smaller the magnet the quicker it cools and the greater the percentage of carbon retained in solution. A good example of this is afforded by the test-pieces of magnet steel from which the demagnetization curves given in this and the previous paper were obtained. The test-pieces are bar magnets of ellipsoidal form with major and minor axes 10·6 cm and 0·51 cm respectively, and it has been observed that when these little pieces of steel are hardened by quenching in an aqueous solution of calcium chloride, the temperature of the steel falls from above the saturation point down to 100° C. in rather less than 2 seconds, less than 1/30th of a minute. Since 25×30 is 750 there is only time for 1/750th part of the surplus carbide present in magnet steel to pass out of solution. In effect the quantity of carbon retained in solution when the steel is cold amounts to 99·9 per cent of the carbon content of the steel, so that the test-pieces when hardened only fall short of the maximum possible potency by an insignificant fraction. In these examples it has been assumed that the critical duration within the mobile region is that indicated by the graphs in Figs. 17 and 18, namely about 25 minutes. The reader has already been warned not to place too much reliance on the numerical accuracy of these two diagrams, and pending some verification of the scanty observational data on which they are founded, the value 25 must be accepted with reserve. But a very large error would have but little effect on the estimated percentage of the carbon content retained in solution. To exaggerate the possible error we might assume that the value 25 is twice the true value. That is to say we might suppose that the critical duration, where complete softening ends and hardening begins, is actually 12·5 minutes. In that case it is easily seen that the percentage for the large magnet would be reduced from 99 to 98, and for the small test-pieces from 99·9 to 99·8. These are relatively small differences and do not affect the proof afforded by the examples that almost all the carbon contained in magnet steel can be retained in solution by the ordinary process of quenching the steel in water.

The numerical examples given in the last paragraph show that in principle the rule for estimating the total amount of carbon which will be retained in solution by any given speed of cooling is of the simplest kind. It may be useful to embody the principle in a formula. Let C denote the total carbon content of the steel, C_a the quantity normally soluble in Alpha iron, and C_s the surplus quantity, all these being conveniently expressed as percentages of the weight of steel. Let r denote the mean rate at which carbon passes from solution to crystal during the time the temperature is falling from the saturation point to 100° C., the value of r depending on the law of cooling, that is to say on the shape of the cooling curve, within the mobile region. Let t be the actual time occupied in cooling the steel through the mobile region when the magnet is quenched for the purpose of hardening. Then the quantity of carbon which will find time to pass out of solution during the quenching will be rt, and putting q for the quantity retained in solution we shall have $q = C - rt$. The constant r may be determined by finding the shortest time of cooling from the saturation point to 100° C. which permits the whole of the surplus carbon to pass out of solution and leaves the steel in the completely softened state. The shortest time is of course the quantity referred to as the critical duration within the mobile region, and denoting it by D we have $r = C_s/D$ so that $q = C - C_s t/D$. But $C_s = C - C_a$ and hence:

$$q = C - (C - C_a)\frac{t}{D}$$

It will be understood that before this formula can be usefully employed in the practice of hardening, trustworthy data must be forthcoming from which to determine the constants involved. Nevertheless, the equation as it stands together with the diagrams given in Figs. 17 and 18 make it possible to follow the sequence of events when a piece of steel cools from a red heat, either slowly to soften it or quickly for hardening. Quantity of surplus carbide, molecular mobility, and the element of time are the factors that count both in hardening and in softening, and it will be seen that already there is promise of a simple arithmetical relation between them. The law by which the rate at which carbon passes from solution to crystal is connected with the temperature of the steel, needs to be known with far greater certainty than it is at present. But it may be anticipated that this and other gaps in our knowledge of the doings of molecules will be filled up before long, and we may therefore look forward with confidence to the day when the age-long mystery surrounding the process of hardening will be finally dispelled.

To understand softening is to understand hardening, for the two are merely opposite extremes of the same process. In giving an account of the softening of steel it has only been possible to watch the solute molecules passing from solution to crystal in vast crowds and to take a statistical view of their doings. Any attempt to trace the course of individual carbide molecules, as they shift from their positions as parts of a solution towards the positions they will occupy as mem-

bers of a crystal, is met by baffling difficulties. One or two details seem clear, however. The molecules do not all begin their passage at the same moment, there is a continuous stream of carbide molecules passing from solution to crystal and, so far as the rather vague experimental evidence affords any indication, it appears that at any given temperature within the mobile region the passage of carbide molecules from one state to the other goes on at a uniform rate from start to finish. Then, again, it is certain that in a solid body like a piece of steel the molecules must be too close together to enable them to move about with freedom, and it seems that translational movements of individual molecules must be greatly hampered by the interference of neighbouring molecules. For this reason the word "mobility" must be regarded as belonging to the statistical view of molecular movements, and must not be allowed to suggest anything of a smoothly flowing nature in the journeyings of individual molecules. What sort of movement is actually involved in the passage of molecules from solution to crystal is not known, but it seems more likely to resemble an obstacle race than a steady flight from one place to another.

Compared with the time occupied by the sluggish carbide molecule in shifting itself from solution to crystal, the conversion of a molecule of Beta iron into the Alpha variety is instantaneous. The re-arrangement of electron orbits which constitutes the allotropic change takes place at lightning speed and, no matter how rapid the cooling may be when a piece of red-hot steel is quenched in cold water, as soon as the temperature in falling reaches the appropriate allotropic change-point, the solvent iron will instantly transform itself into the Alpha or magnetic variety. Nothing we can do in the way of sudden cooling can prevent that transformation, and the moment it occurs the solute carbide molecules find themselves urged to pass out of solution. But the obstacle race from solution to crystal has scarcely had time to begin before the rapidly cooling steel is cold and mobility has vanished. Deprived of their freedom the carbide molecules have nothing for it but to stop where they are, in the positions characteristic of the state of solution. What keeps them there, whether they are in any kind of temporary equilibrium, stable or unstable, and what proportion of the total number of carbide molecules will stay permanently in the positions of solution, are all questions of deep interest, to be answered it may be hoped by research. But no matter what the answers may be the central fact will remain unshaken. So long as the carbide molecules can be induced to remain in what appears to be a state of solution the potency-giving pattern will be there and the hardened steel will be fit for a permanent magnet. Abnormal as the solution appears to be, it is none the less effective in giving potency to the magnetic mechanism.

(16) The Gradual Decay of Hardened Steel.

Nothing looks more likely to be lasting than a piece of hardened steel, and without giving a thought to molecular mobility we should naturally expect the steel to retain its high degree of potency for ever. But it is only necessary to make a few measurements of coercive force at suitable intervals of time shortly after the hardening of a magnet, to discover the disconcerting fact that from the moment the steel is hardened the potency begins to decay, and with the loss of potency the inherent power of the steel to maintain magnetic energy gradually decreases.

When it was first discovered that permanent magnets grow weaker with age, it seems to have been tacitly assumed that it was the magnetization alone which decayed, the steel itself being apparently regarded as immutable—at all events at ordinary room temperatures. If that conception of hardened steel survives, the evidence given in the present section will finally dispose of it, for it will be shown that what is done by plunging red-hot steel into a cooling bath immediately begins to come undone when the hardening process is at an end. Moreover, the undoing goes on year after year and so

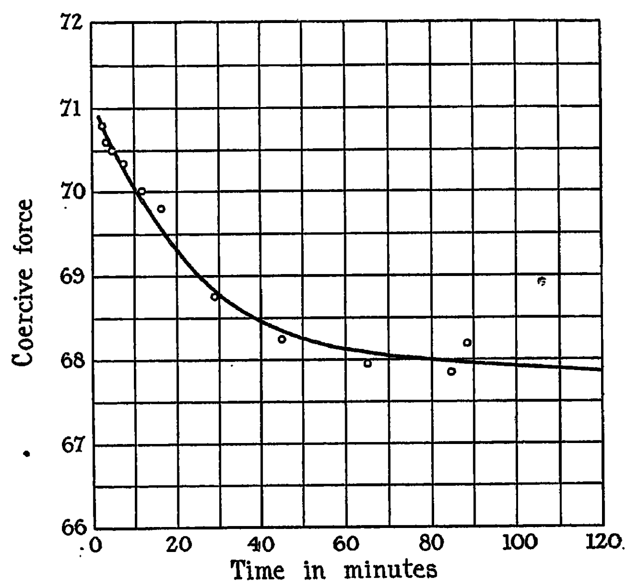

Fig. 19.—Decay in the potency of hardened steel. Curve showing the rapid loss of coercive force in tungsten magnet steel immediately after the hardening.

far as the investigation has gone at present, there is no sign of an approach to equilibrium. However it may be explained, there is no longer any doubt of the fact; the potency created in the steel by the hardening slowly disappears as time goes on.

That hardened steel should suffer a gradual loss of potency and hardness seems a foregone conclusion if steel is a solution of carbide molecules in iron. For the hardened steel certainly contains more carbon than is naturally soluble in Alpha iron at room temperature, and since the resulting condition must necessarily be one of instability, the tendency will be for carbon to pass from solution to crystal until the solution is in equilibrium. It follows that so long as there is the slightest molecular mobility in the solid steel, the dissolved carbide molecules must inevitably pass out of solution, however slowly; and to the extent that they do so, there must be a loss of potency and hardness.

It would seem that hardly anyone engaged in making permanent magnets could fail to notice the gradual

falling off in coercive force which takes place after the steel has been hardened, but although the fact must surely be known, it does not seem to have engaged the

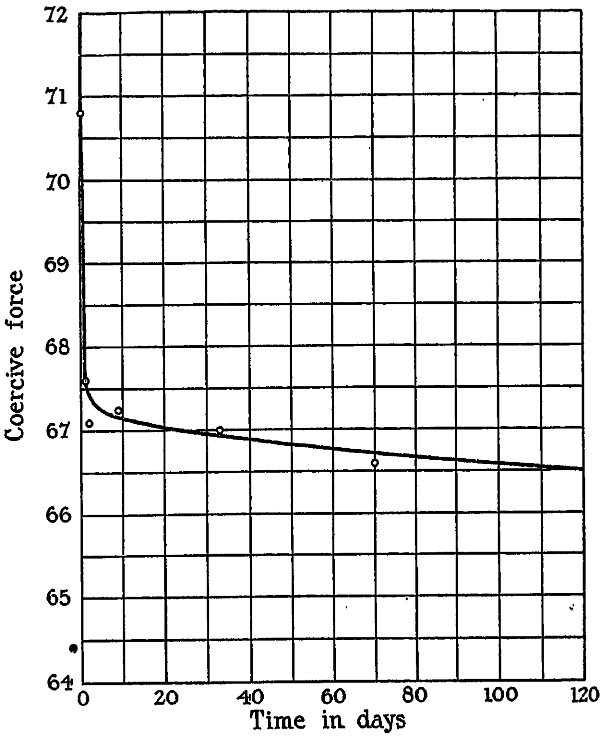

FIG. 20.—Decay in the potency of hardened steel. Curve showing the continued loss of coercive force in tungsten magnet steel during 120 days after the hardening.

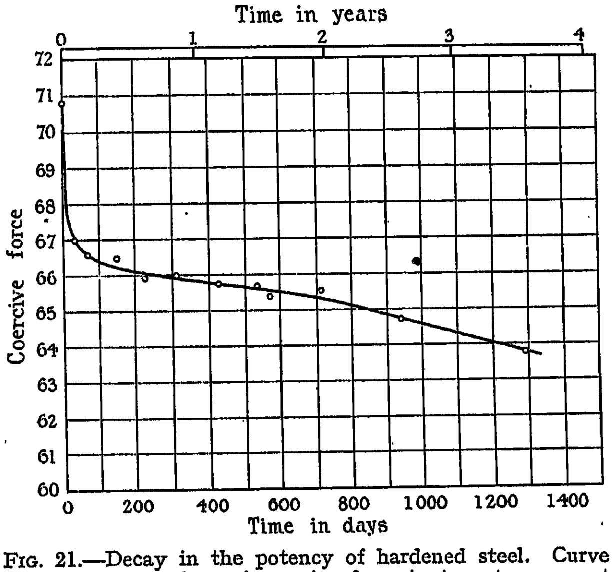

FIG. 21.—Decay in the potency of hardened steel. Curve showing the loss of coercive force in tungsten magnet steel going on for $3\frac{1}{2}$ years after the hardening.

attention of the metallurgist. At all events nothing relating to the subject appears to have been published, and the lack of information on a matter so closely connected with the constancy of the permanent magnet led the author, some years since, to set on foot a continuous series of tests of the coercive force of magnets from the time of hardening onwards. The method of experiment has been to measure the coercive force of a hardened steel bar of ellipsoidal form at lengthening intervals of time. Each test consists in first magnetizing the steel to the full extent and then making an accurate magnetometer measurement of the Hopkinsonian coercive force of the specimen. It will be noticed that by complete re-magnetization before

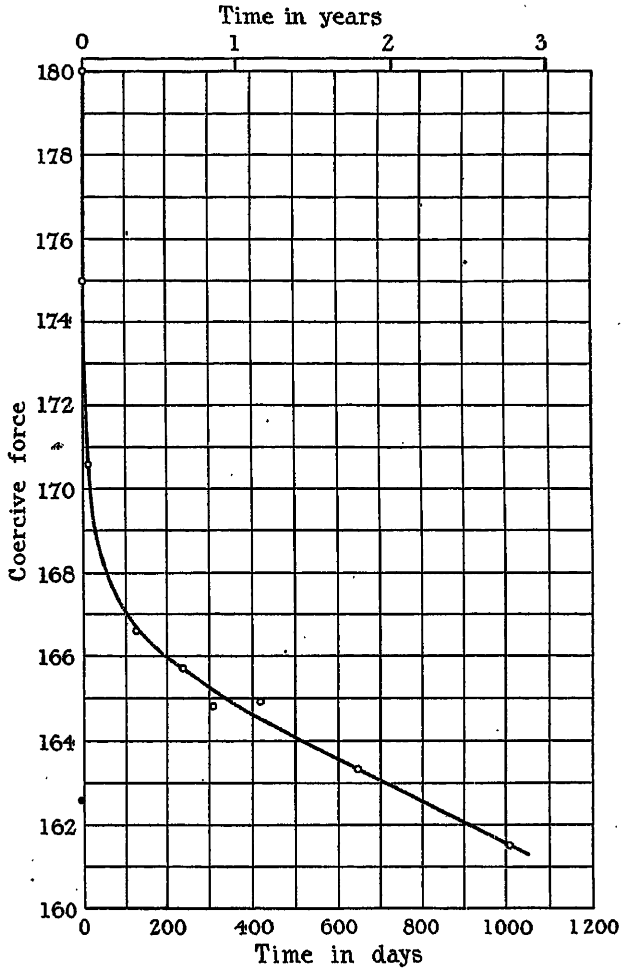

FIG. 22.—Decay in the potency of hardened steel. Curve showing the loss of coercive force in cobalt magnet steel going on for 3 years after the hardening.

each test all effects other than changes in the steel itself are eliminated. The magnetometer readings of coercive force are made to the nearest tenth of a unit, and each recorded value is the mean of at least two, and in most cases four, independent tests, these being made with the magnetization first in one direction along the steel bar and then in the other. All the tests are made with the steel at room temperature. In the intervals between the tests the specimens under observation are subject only to the small temperature variations of the air in the experimental room, the average temperature being about 18° C. and the maxi-

mum and minimum temperatures in summer and winter roughly 30° and 12° C. Tungsten steel and cobalt steel have been under observation in this way during the last four years. The tests are being continued, but they already afford convincing evidence that the hardened state in magnet steel is far from being a permanent condition.

The coercive force of hardened steel has its maximum value immediately after the hardening, and for the first hour or so afterwards a very rapid decrease takes place. But, as time goes on, the rate of change gradually diminishes, tending to become more or less constant after a month or two. An example of the gradual loss of potency is shown in Figs. 19, 20 and 21. These three diagrams relate to an ellipsoidal bar of tungsten steel which, having been hardened on the 20th November, 1920, has been kept under observation from that date to the present time, Fig. 21 recording the progress of decay from the day the steel was hardened up to June, 1924. The irregularities shown by the test points must not pass unnoticed. Many of them are too large to be explained away as observational errors, and some other cause must be looked for. We shall consider these apparent discrepancies again after examining the decay curves obtained from cobalt magnet steel, and in the meantime the smooth curves shown in the diagrams must be regarded as representing merely the general trend of decay in hardened tungsten magnet steel.

For the purpose of observation and measurement cobalt steel provides a better material for experiment than tungsten steel, since as a result of the greater potency of cobalt steel the phenomena of decay occur on a much larger scale. A curve of decay obtained from a typical specimen of cobalt magnet steel is given in Fig. 22. Fuller information is available in this instance, complete demagnetization curves having been obtained from the test specimen on each occasion when a decay test was made. Two of these curves are shown in Fig. 23 to illustrate the dependence of available energy on potency. The useful energy which the steel can maintain naturally falls off as the potency decays.

It will be noticed that some irregularity in the progress of decay is indicated by the position of a few of the test-points in Fig. 22. A clue to the origin of irregularities of this kind has at length been discovered by an examination of the decay tests made on another sample of cobalt magnet steel. It so happened that in this particular specimen a very noticeable *increase* in coercive force took place in the interval between two successive tests, and since it seemed obvious that something unusual was going on, the succeeding tests were made at intervals of two or three months, instead of adhering to the course adopted in other cases of increasing the intervals to six and twelve months as the rapidity of decay declined. The more frequent observations disclosed the fact that the general course of decay was accompanied by a cyclic change of decreasing amplitude. By the time the magnet had been under observation for several years, it became clear that the oscillation in the decay curve was a seasonal one with a complete period of twelve months. When this fact is taken into account all the test-points easily fall into their right places on a wavy line which represents the progress of decay combined with a seasonal oscillation of rapidly decreasing amplitude. This remarkable curve is shown in Fig. 24. The coercive force immediately after hardening the magnet

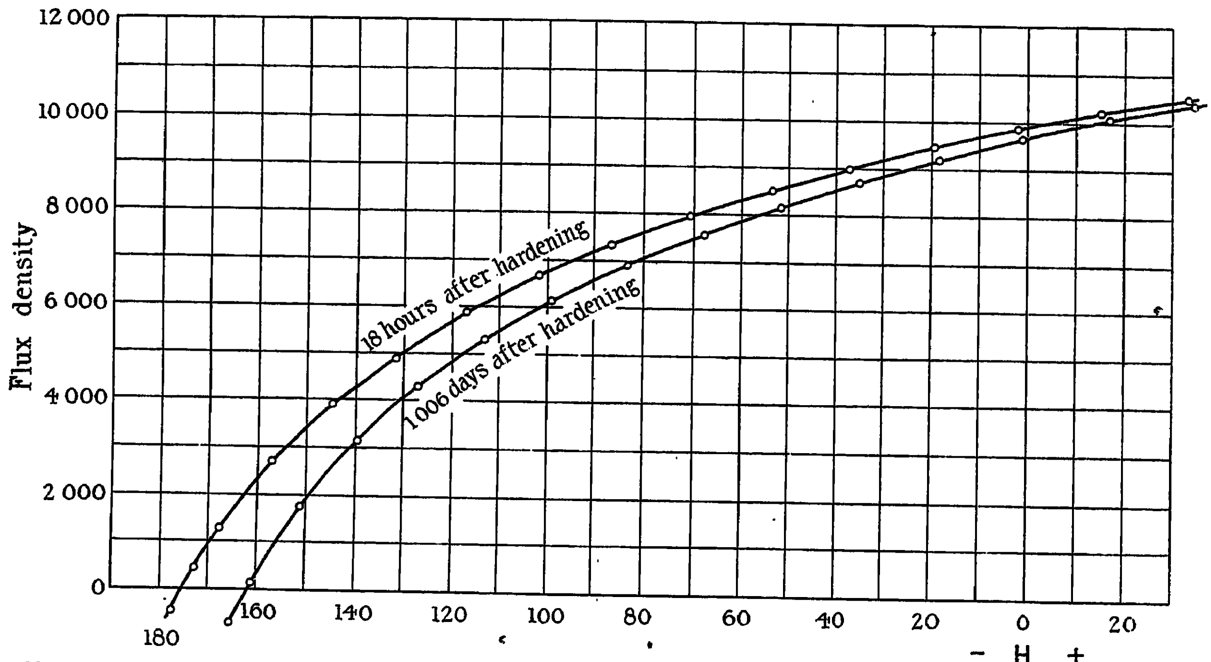

FIG. 23.—Decay in the potency of hardened steel. Demagnetization curves obtained from a specimen of hardened cobalt magnet steel, 1 day and 1 006 days after the hardening.

was 180·0, and the test made after the lapse of 4·4 years showed that the coercive force had declined to 161·8 in that time, a loss of 18·2 units or 10 per cent.

Seasonal changes having been recognized in cobalt steel it was natural to look for them in tungsten steel. Evidence of their existence has been sought by plotting the test-points recorded in Fig. 21 to a magnified vertical scale, and then completing the diagram by a line following the course indicated by the relative positions of the test-points, so far as it was possible to do so without

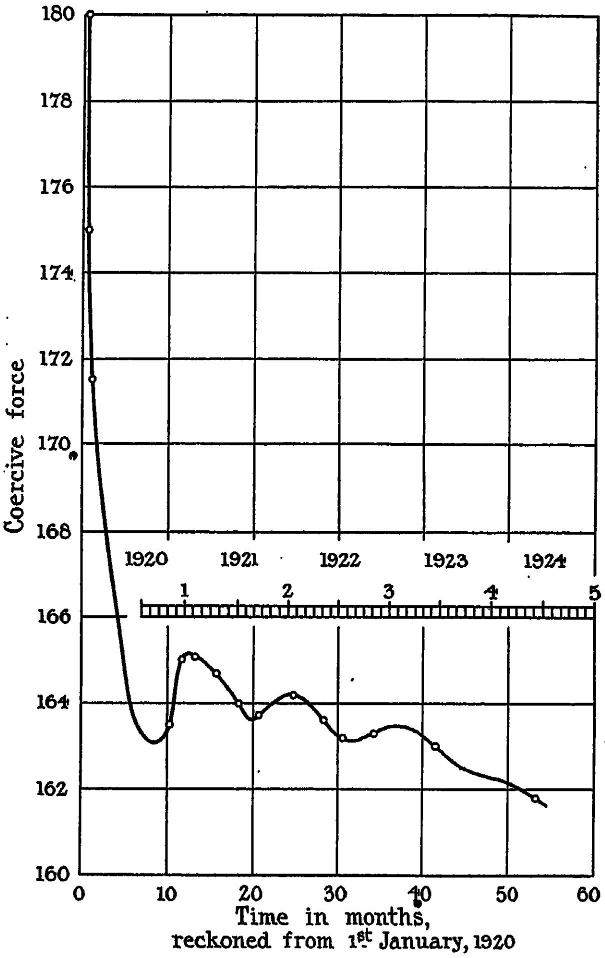

FIG. 24.—Decay in the potency of hardened steel. Curve obtained from a specimen of cobalt magnet steel, showing a seasonal change in the rate of decay during the first few years after the hardening.

making sudden changes in direction. The graph constructed in this way is reproduced in Fig. 25 and it will be seen that the test-points, which at a first examination showed numerous apparent errors, are actually quite consistent with the occurrence of a seasonal oscillation in the progress of decay in tungsten steel.

The continuous falling off in the coercive force of hardened magnet steel, demonstrated by the tests recorded in the diagrams, can only be attributed to the passage of carbide molecules out of solution. From the general course of the curves of decay it is clear that immediately after the hardening there is a rush of solute molecules out of solution, the coercive force decreasing by from 6 to 8 per cent in the course of the first 100 hours. With the lapse of time the progress of decay has tended to become a nearly uniform decline, apart from the influence of the seasonal changes. Within a year from the hardening the rate of decay in each of the specimens of steel under observation settled down to a more or less steady value, which has been maintained for three or four years without any noticeable abatement, the steady rate of decay being many thousand times smaller than the rate immediately after the hardening.

The rapid initial effect, followed by slow but persistent decay, suggests that the change from solution to crystal takes place in two distinct stages. In the

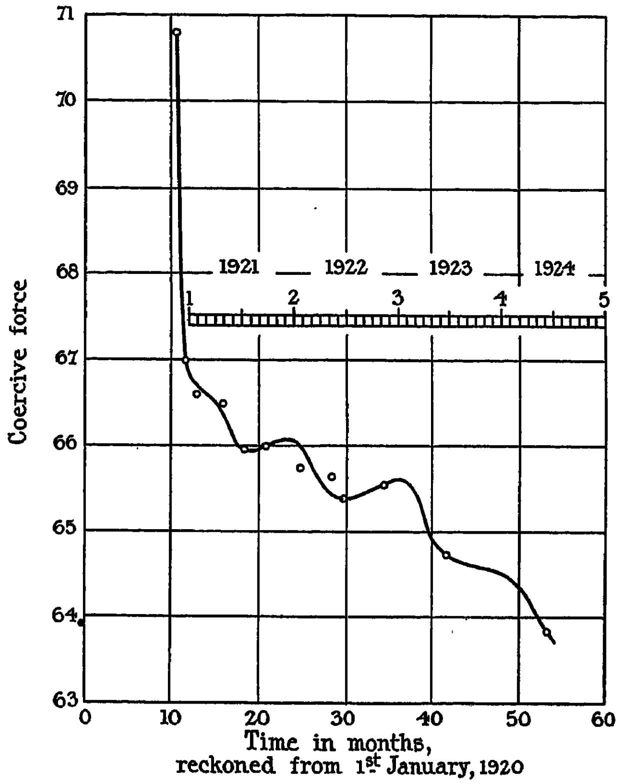

FIG. 25.—Decay in the potency of hardened steel. The curve given in Fig. 21 for tungsten magnet steel redrawn on the assumption of a seasonal change similar to that shown in Fig. 24.

first stage we may imagine the solute molecules to be leaving their solution positions and drifting into an intermediate condition of temporary independence, half way between solution and crystal. Released from the bonds of solution the molecules would be free to form other ties, and the second stage would consist in molecules coming together to form elementary crystals. At first there would be nothing to prevent a rush of molecules into the intermediate state, but as the sort of half-way house became crowded, molecules would experience more and more difficulty in leaving their solution positions. To account for the diminution in

the rate of decay we must suppose that the assembling of molecules as crystals relieves the crowding of the intermediate state, and on that assumption the rate at which molecules would pass into the half-way house would ultimately be reduced to an equality with the rate at which other molecules, already in a condition of independence, were assembling themselves as crystals. This would be the state of affairs when the decline of coercive force had settled down to a steady rate.

The intervention of the seasonal change makes it difficult to compute the steady rate of decay with any precision. So far as it is possible to judge from the curves of decay, the coercive force is at present decreasing at the rate of about 2·0 units a year in the specimens of cobalt magnet steel, and roughly 0·8 units per annum in the tungsten steel. These figures give a ratio of 2·5 and it is of interest to note that the figures for the initial values of the coercive force, namely 180 and 71, are almost in the same proportion. The inference must be that the carbide molecules in these two kinds of steel pass out of solution at much the same rate.

There is at present no indication of a falling off in the rate of decay but it is difficult to believe that it can continue unabated. Unless something unforeseen puts a stop to the progress of decay the whole of the surplus carbide will pass out of solution and the steel will ultimately return to the softened state. At the present time after four years of decay the coercive force of the cobalt steel is about 162 and that of the tungsten steel about 64. In the softened state the coercive force would be roughly 30 and 16 in these two steels, so that the ultimate loss, reckoning from the present condition, would be 132 and 48 units respectively. Hence if the present steady rates of decay were to continue unchanged, the cobalt steel would be completely softened in 132/2, or 66 years; and the tungsten steel would be reduced to the same condition in 48/0·8 or 60 years. Adding 4 years for the time already elapsed, it appears that the whole of the surplus carbide in hardened magnet steel might pass out of solution in the course of about 70 years from the time of hardening. But if the hardened condition of steel lasts no longer than that, the gradual softening with time could scarcely have remained undiscovered,* and the probability is that the rate at which the carbide molecules pass out of solution will fall off as the amount of carbide remaining in solution decreases. Assuming this as the probable course of events, the gradual change in the steel from the hardened condition to the softened state might easily occupy many times 70 years, if indeed any finite limit can be assigned to the duration of a process which would be going on at an ever lessening rate.

So far the seasonal oscillation of rapidly diminishing amplitude remains unexplained. We have learnt to associate oscillation with the exchange of energy between elasticity and inertia, or between electrostatic capacity and inductance, or more generally to the exchange between potential energy and kinetic energy, and when the amplitude decreases we know that some of the energy is being dissipated as heat or at all events escaping from the oscillatory system by some means or other. It is strange to find the well-understood phenomena of oscillation reproduced or imitated in a molecular disturbance where it would be least expected, and with the enormous periodic time of 365 days. That the seasonal effect is connected in some way with temperature variation may be taken for granted, but beyond this all is obscure. The amplitude of the oscillation decreases so rapidly that within four years from the time of hardening the effect has become barely perceptible and there can hardly be a doubt that from four years onwards the course of the decay curve will be steadily downwards without any noticeable oscillation.

The investigation thus briefly recorded leaves us in no doubt on the main point. Steel, magnet steel at all events, which has been hardened by rapid cooling from a red heat is not the immutable substance it appears to be. On the contrary, steel which has been hardened in that way in order to compel the whole of the carbon to remain in solution in Alpha iron, is essentially unstable. The sudden cooling has no sooner ended than decay sets in, the potency, and presumably the hardness, gradually decreasing as time goes on. After four years the loss of potency is found to be going on slowly, steadily and without any sign of coming to an end. Nothing short of continuous observation carried on for many years can tell us when and at what point this loss of potency, this gradual change from hardness to softness, from solution to crystal, is going to stop. So far as can be told at present, there seems no reason to anticipate an end to decay until the whole of the surplus carbon having at long last been transferred from solution to crystal the steel becomes a solution of just so much carbide in Alpha iron as can be retained in stable equilibrium.

The effect which the decay in the potency of hardened steel has on the magnetic power of a permanent magnet, and the extent to which the loss of potency can be forestalled, will be considered in Part IV under the heading of Ageing.

(17) The Essential Molecular Structure for a Permanent Magnet.

The preceding sections have been written in the belief that the readiest way to obtain a clear understanding of the behaviour of magnet steel at its best is to know what it might do at its worst. Much space has therefore been devoted to the various causes of magnetic weakness. In Gamma iron the potency-giving molecules decompose; in ultra-heated steel some of the solvent iron persists in the non-magnetic state; in hardened steel the potency decays with time. Each of these defects involves a loss of useful magnetic power, but after all they are matters incidental to the making of magnet steel or to the subsequent life of the steel as a permanent magnet. They are not the essentials of permanent magnetism, and after a long sojourn in the metallurgical jungle we emerge at last to obtain a clearer view of the magnetic mechanism which constitutes the essential magnet.

If the broad principle finds acceptance, that the magnetic potency of steel has its origin in the molecular pattern peculiar to the state of solution, then it will be acknowledged that, so far as the magnetic mechanism

* It would be interesting to learn whether an indication of softening with age has ever been observed in such things as swords or carpenter's tools, which are not infrequently preserved for generations.

is concerned, an absolutely uniform solution of potency-giving carbide molecules in Alpha iron would provide all that is essential in a permanent magnet. The structure of a solution being invisible in even the most powerful microscope, the structural appearances sometimes seen in hardened steel must be attributed to want of homogeneity, to incomplete solution due to imperfect hardening, or to decomposition, for unless particular care had been exercised in the choice of the specimen the steel would almost certainly be in a spoiled condition.* Any visible structures, due to such causes as these, far from being signs of magnetic power, would in all probability be impediments to its propagation and we may be sure that anything seen is not the essential mechanism.

But the solvent itself, Alpha iron, has a structure. Solid iron in all its varieties is crystalline, and if the picture of a permanent magnet as a solid solution is to resemble reality, the nature of the crystalline structure and the way it comes about must be borne in mind. Any metal which has solidified from the molten state is a crystalline substance. That is to say it is built up from elements each consisting of a few molecules forming some particular kind of orderly group, bound together by forces which compel them to assume that order and no other. This orderly structure having been initiated at some spot, some nucleus, which formed a convenient site for the assembling of the first elementary group, the conditions at that spot determined the angular aspect † in which the first element assembled itself, and thereafter all the elements, in obedience to the law of crystalline growth, were compelled to adopt the same aspect. The crystal elements are like the bricks in a plain wall, where the angular aspect is determined by the laying of the first brick.

Under normal conditions there are innumerable sites where crystal growth can begin, and each site or nucleus will determine once for all the aspect of the crystalline structure that grows up round about it, the aspect of the structure not being influenced in any way by the different aspects initiated at neighbouring sites. In the same way a number of bricklayers might begin building detached portions of a wall at all sorts of angles and inclinations. After a time—in practice quite a long time—the several portions of growing wall would meet, and as the result of the random choice of aspects, any orderly linking up of the pieces of wall would be impossible. The boundary between one piece of wall and another would be an irregular, badly fitting joint, and the most a bricklayer could do would be to fill in all the joints with bits of broken brick and mortar. Something like this happens with the several crystal structures. They grow element by element, brick by brick, until neighbouring structures come up against each other and the entire space becomes filled with the different crystal growths, each growth having begun at its own nucleus and preserved the angular aspect that had its origin there. As the result of the different aspects, the meeting places of adjacent growths will form rough joints of somewhat irregular outline, and it is even supposed that the joints are filled in with stray molecules of iron and impurities which play the part of the bricklayer's debris of broken brick and mortar.* The general appearance of the entire crystalline structure, if the individual crystal growths were large enough to be seen, would be something like that sketched in Fig. 26, the extent of the growth from each nucleus being marked by a boundary line indicating the irregular joint between adjacent growths. Each area is described by metallurgists as a crystal grain, or sometimes simply as a crystal.†

The general lack of visible structure in the interior of perfectly hardened magnet steel makes it difficult, if not impossible, to determine the size of the crystal grains of Alpha iron. Mere size is, however, immaterial.

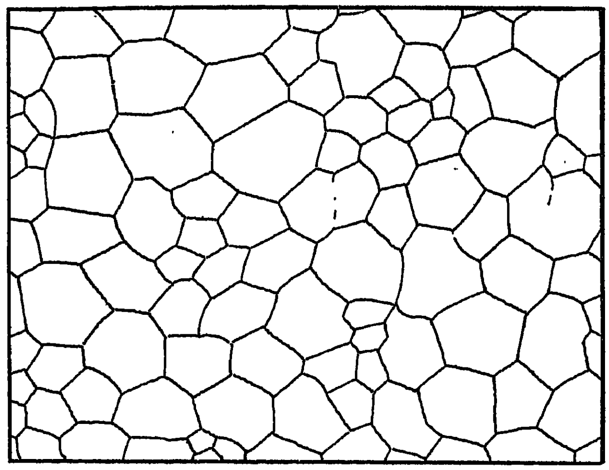

FIG. 26.—Sketch showing how crystal growth, starting from a number of originating sites or nuclei, results in a number of crystal grains, each restricted in size and shape by the growth of neighbouring grains. (Author, from a microphotograph by Sherard Cowper-Coles.)

Visible or invisible the crystal grains are there as the necessary outcome of the process of crystalline growth from a number of sites or nuclei. As a solution, therefore, a piece of hardened magnet steel is not a single entity, but an assemblage of innumerable crystal grains of Alpha iron each containing molecules of carbide in solution. Each grain is a homogenous solution, but since the distribution of carbon throughout a piece of magnet steel is never perfectly uniform the different crystal grains will vary in the proportions of solute carbide which they contain, and consequently the crystal grains will differ in their potency.

Within each crystal grain lies the magnetic generating mechanism on which attention has been concentrated in this and the previous paper. It is an affair of mole-

* In making experiments on tungsten steels it seems to have been the general practice of metallurgists to begin by heating the test specimens for an hour or more at some temperature between 900° and 1 000°, thus partially spoiling the steel—and the experiment.

† Orientation would be a better word than aspect, for the uniform angular arrangement of crystal growth. But in a paper on permanent magnets orientation stands for the deflection of the magnetic molecules by a magnetizing field, and to avoid confusion the word "aspect" is applied here to the crystal structure.

* The "amorphous layer" of Professor Beilby.

† The word "crystal" calls up a mental picture of a body of symmetrical shape bounded by flat surfaces. These wonderfully beautiful forms are, however, only possible when there is nothing whatever to interfere with orderly growth. Where crystal growth springs simultaneously from several adjacent nuclei, as in the case considered in the text, each crystal grain is hampered by the proximity of its neighbours and in the end its growth is confined to filling in any space that may still be available. The grain is a crystal in a sense; but it is a thwarted crystal, robbed of the beauty of symmetry in outward form.

cules, and relatively few molecules are needed to construct a complete microcosm of the permanent magnet. Assuming that by some means or other the magnetic molecules have been arranged in the required pattern, the potency-giving pattern, Ewing's model shows that less than 100 molecules of Alpha iron would suffice. But to include within the microcosm the means by which that pattern is created there must be a sufficient number of molecules of solvent iron and solute carbide to create the essential properties of a solution. Bearing this in mind, we may imagine a microcosm consisting of 1 000 000 molecules of Alpha iron as solvent, in which are dissolved 39 000 molecules of carbide of tungsten, WC, and 39 000 molecules of carbide of iron, Fe_3C, those being in round numbers the proportions of the best tungsten magnet steel. Being a solution of carbides in Alpha iron, the 1 078 000 molecules would arrange themselves in the particular pattern that creates potency. So small a number of molecules as 1 078 000 would constitute an inconceivably minute crystal grain, yet it would be endowed with the inherent magnetism and the potency of hardened magnet steel, and would behave in all respects, save one, like a permanent magnet.

The one exception just referred to arises from the fact that within an individual grain the crystalline structure has but one angular aspect, whereas a permanent magnet is composed of an immense number of crystal grains of every variety of aspect. Now in the single crystal grain with its uniformity of aspect, it is almost certain that the potency would be found to depend on the inclination of the axis of magnetization with respect to the crystalline aspect, and hence the power of the crystal grain as a permanent magnet would depend to some extent on the direction in which we chose to magnetize it. But in a piece of steel containing a large number of crystal grains, the resultant potency is the average of the various individual potencies of a number of grains of every variety of aspect, and being an average of that kind the resultant potency of the steel is, of course, the same in all directions. Apart from that one structural difference and the further fact, already referred to, that in the magnet the crystal grains would be more than likely to contain different proportions of carbon, the permanent magnet and the microcosm of 1 078 000 molecules would be indistinguishable in their magnetic properties.

(18) Conclusion.

Returning to the point from which we set out on our metallurgical journey, and recalling the extraordinary complexity arising from the allotropy of iron, to say nothing of the precarious existence of carbide molecules in Gamma iron, it could hardly have been anticipated that in the final view hardened magnet steel would take on so simple an appearance. But simplicity has only been arrived at by imagining a perfection of homogeneity beyond anything attained in steel-making, by disregarding many subsidiary matters and adhering, so far as possible, to essentials. Even so, the simplicity of the picture is to some extent an illusion, for wrapped up in the essentials are some of the most difficult of unsolved problems, such as the nature of solution, the character of the mechanism by which the state of solution creates magnetic potency, and, above all, the problem of the atom with its electrons whirling in planetary orbits.

In bringing this account of the metallurgy of magnet steel to a conclusion the author is only too conscious how much it falls short of what an exposition of so tangled a subject should be. At the risk of leaving out some vital link in the chain, much that forms the common stock of metallurgical knowledge has been omitted in order to attend to matters more directly bearing on the magnetic properties of steel. Tungsten steel has been taken as the typical magnet steel. Cobalt magnet steel behaves in much the same way, but on an exaggerated scale. Want of space has prevented separate notice of its distinctive features; its phenomenal potency—when made in the laboratory; its excessive degradation by spoiling—when made in the steelworks. Other omissions, conscious and unconscious, can only be set down to want of knowledge.

Yet, with all omissions, it is hoped that the picture of magnet steel has been so presented that it can be seen as a whole. It is so easy to miss seeing the wood because of the trees, and there never was a subject more crowded with trees and undergrowth.

PART IV.

PERMANENT MAGNETS IN THE MAKING.

(19) The Mediæval Art and Mystery of the Magnet Maker.

> "The compass needle, being the most admirable and useful instrument in the whole world, is so bungerly and absurdly contrived as nothing more."
> *Barlowe's Magnetical Advertisements*, 1616.

Industries rooted in tradition naturally lag behind and although three hundred years have gone by since Barlowe deplored the imperfections of the permanent magnet as he knew it, his apt words apply to much that goes on to-day in making magnets. Yet in some ways things have changed. There has, of course, been a vast extension in utility. Permanent magnetism serves many different purposes and the permanent magnet has become an indispensable adjunct in engineering. But with this incentive to progress the making of a magnet is still largely governed by rule-of-thumb notions as it was in Barlowe's time. Bungerly it was, bungerly it remains.

The deadening effect of tradition is not solely to blame for this lack of progress in a small but important industry. Something must be attributed to the subordinate position which the industry occupies. The manufacture of permanent magnets is not carried on as a separate branch of engineering like the making of other small adjuncts such as bolts and nuts or ball bearings. Permanent magnets are either made by the steelmaker for the user, or the user himself makes them as one of the components of the apparatus for which they are intended. As an industry, therefore, magnet-making rather falls between two stools and the

progress that comes from concentration of effort is lacking; for wherever the magnets are made, their manufacture is but a small branch subsidiary to the main stem. The natural consequence is that permanent magnets are for the most part made in the light of that kind of vague knowledge that leads nowhere.

The object of the present paper is to assist the magnet maker, whoever he may be, in overcoming some of the difficulties that beset him. It is hoped that in the following pages a useful light may be thrown on some of the many obscurities and particularly on those darker places in the way where the present writer, as one of the mediæval fraternity of magnet makers, has constantly found himself stumbling. Attention has first been directed to the metallurgical facts of magnet steel, in the belief that future improvement in the art of magnet-making must be founded on a better knowledge of the raw material than has hitherto been available. Consideration will now be given to the practical bearing of some of the subjects dealt with in Part III. In addition to matters relating to present practice, a novel departure in making permanent magnets by casting them in ordinary magnet steel will be described, and lastly some of the unsolved problems to which future research might well be devoted will be briefly referred to.

The earliest form of permanent magnet made of steel was the compass needle, and the art of magnet-making may be said to date from the invention of the mariner's compass. Just when that was no one knows, but the permanent magnet certainly antedates such things as the electric telegraph and the dynamo by untold centuries, and it is by no means surprising to find traces of its early origin still clinging to it. Throughout the making of a magnet from the mixing and melting of the ingredients of the steel in a crucible, to the hardening of the magnet, at every stage there is something to remind us of a mediæval art and mystery. To watch steel being poured from a crucible into an ingot mould or to see a workman harden a magnet is to live again in the middle ages. Of late years the metallurgical chemist and the pyrometer have made good progress in the uphill task of replacing tradition and rule-of-thumb by knowledge, but speaking generally the manufacture of permanent magnets, including the making of magnet steel, is still in a backward state and contrasts unfavourably with the precision and uniformity that has been attained elsewhere in modern engineering practice by the application of scientific method.

Up to the present time magnet steel has invariably been produced in the form of rolled bar, the common practice being to melt from 60 to 80 lb. of metal in a crucible and pour it into an ingot mould. The ingot, having been reheated and reduced to a smaller section by cogging, is finally rolled down to the particular section required by the magnet maker. A ton of steel produced in this way is the product of between 30 and 40 crucibles and, not unnaturally, variations in composition are frequent, more particularly in the vital matter of carbon content. The figures given in Table 8 show the extent of the irregularities that occur in practice. The wide variations in carbon above and below the specified percentage are quite enough to condemn the traditional method of melting steel by driblets in little crucibles.

Uniformity in composition can only be ensured by melting steel in bulk, a ton or more at a time. Mainly as the result of the introduction of electric furnaces, this improvement in practice has been generally adopted for steels which are used in large quantities, but the comparatively small demand and the different compositions which magnet makers, rightly or wrongly, believe to be necessary, have afforded little inducement to the steelmaker to mix and melt magnet steel in bulk. The time is ripe for the change, and so far as tungsten magnet steel is concerned there seems no reason why the optimum composition given in Section (21) should not be equally applicable to all purposes. Assuming the optimum composition to be generally adopted by magnet makers, the steelmaker would incur

TABLE 8.

Reference		Carbon		Tungsten	
Year	No.	Specified	Found by analysis	Specified	Found by analysis
1917	1	0·70	0·522	5·0	5·27
1917	2	0·70	0·665	5·0	5·38
1917	3	0·70	0·562	5·0	5·41
1918	4	0·70	0·661	5·0	6·24
1918	5	0·70	0·860	5·0	5·85
1918	6	0·70	0·691	5·0	6·24
1919	7	0·70	0·889	5·0	5·54
1919	8	0·70	0·776	5·0	5·54
1919	9	0·70	0·712	5·0	5·52
1919	10	0·70	0·703	5·0	4·59
1920	11	0·70	0·633	6·0	6·03
1920	12	0·70	0·726	6·0	6·02
1920	13	0·70	0·804	6·0	5·93
1921	14	0·70	0·599	6·0	6·29
1921	15	0·70	0·725	6·0	6·13
1921	16	0·70	0·714	6·0	6·25
1921	17	0·70	0·653	6·0	6·27

Analyses of various batches of rolled tungsten magnet steel supplied by four Sheffield steelmakers.

no risk in melting steel of that composition in bulk; the resulting ingots being subsequently rolled down to suit the requirements of individual users.

A more insidious fault than want of uniformity in composition is the spoiled state in which rolled magnet steel leaves the steelworks. As the several processes of manufacture are conducted at present, spoiled magnet steel is the rule, unspoiled steel the exception. In this respect there is nothing to choose between one steelworks and another, common practice in making magnet steel being at fault.

Another troublesome defect in magnet steel is the presence of incipient cracks, or if not actual cracks a weakness of structure which easily gives rise to cracks. The final cause of cracking is, of course, the violent process of hardening by sudden cooling, but different

lengths of steel which have been rolled at one time are often found to differ greatly in the tendency to crack in hardening. This clearly indicates some occult structural weakness in the individual length of rolled steel, a weakness which might easily arise if the rolling ended at an unduly low temperature.

Having survived the perils of the steelworks, more or less impaired in magnetic quality and mechanical strength, the lengths of rolled steel become the raw material of the magnet maker. The first step is to cut up the rolled bar into short pieces of the appropriate length for a magnet. The magnet lengths are then heated to about 900° C. and forged or bent to the required shape. After trimming the ends and drilling holes for fixing screws, if they are required, the shaped pieces are hardened from a temperature of about 850° C. by quenching them in cool water or oil. The hardened pieces are then magnetized, the method of magnetization depending on the shape of the magnet. With a suitable outline, the magnet can be included in the magnetic circuit of a powerful electromagnet; but if the shape given to the steel does not lend itself to that simple and expeditious method, a temporary exciting coil must be wound round the magnet and a current of the necessary strength passed through it. In the author's practice the actual winding of a coil is avoided, the exciting coil consisting of a number of detachable links which are readily removed for the insertion of the magnet. After magnetization the magnet is usually subjected to some treatment intended to secure constancy of magnetic power.

The mischief done to the steel in making a magnet is confined to the processes of forging and hardening. It is impracticable to forge or even to bend a piece of rolled magnet steel without heating it to a temperature within the danger zone, and consequently some further degradation by spoiling inevitably occurs. But the spoiling at this stage is small compared with what the steel has already suffered in the steelworks, and by limiting the duration of heating the spoiling can be reduced to a negligible amount. The temperature to which the steel must be heated for the purpose of hardening is also within the danger zone, but here again spoiling is easily made negligible by limiting the duration of heating. Inherent in the process of hardening by rapid cooling is the risk of cracking and distortion, evils which after centuries of experience remain unmastered.

This brief history of the production of a magnet, from crucible to quenching bath, is enough to show the need for improvement in manufacture. Erratic composition, excessive spoiling, and the liability to cracking, are the outstanding defects. As regards the first, no one looks for perfect uniformity of composition, but it ought to be possible for the steelmaker to confine the errors within much narrower limits than he does at present. The prevention of spoiling during the manufacture of magnet steel is another matter for the steelmaker. The remedy has already been referred to in Section (13). It is a problem in heat treatment and will be readily solved when once it is attacked with knowledge. Cracking and distortion go together. Both need scientific investigation but the subject is full of difficulty, and research is likely to be prolonged. To find remedies for these evils is eminently a problem for industrial research—it will never be solved by the nostrums of the toolmaker.

Fortunately practice has a way of making light of the most baffling difficulties, and the magnet maker often manages to turn out a few wonderfully good magnets, in addition to a vast number of indifferent ones and many wasters for the scrap heap. Success is contingent on a number of chances occurring one after the other. If the steelmaker happens to mix the ingredients of magnet steel in the right proportions; if the carbon happens to distribute itself uniformly; if the steel when heated for the rolling happens to escape from the danger zone into the region of temperature in which restoration takes place; if the magnet maker happens to succeed in persuading all the potency-giving carbide molecules to remain in an abnormal state of solution in Alpha iron; and lastly if the magnet, in hardening, happens not to crack—if all these things happen in due order then a powerful permanent magnet is forthcoming.

All this relates to the practice of making permanent magnets from bars of rolled steel. The drawbacks incidental to rolling the steel and forging the magnet to shape, including nearly all the degradation by spoiling, would be gone if in place of the casting of ingots, followed by rolling and forging, the molten steel were to be cast at once in the shape of a magnet, pole pieces and all. In Section (23) it will be shown that cast magnets of ordinary magnet steel present many points of advantage over magnets of rolled steel and are in no way inferior in magnetic power.

Whether a magnet is to be a casting or a piece of rolled bar, the first step is the same. The designer must choose the kind of steel and the percentage composition that answers best to his requirement. These matters will therefore next engage our attention.

(20) The Cost of Magnetic Energy: Carbon Steel, Tungsten Steel and Cobalt Steel Compared.

The choice of steel for permanent magnets is governed by several considerations. Economy in cost is often the deciding factor, but even when some technical advantage to be gained outweighs economy, it is useful to compare the gain with the additional cost, provided the magnets are large enough or numerous enough to justify such a comparison. We shall, therefore, begin with the purely economic aspect of the problem as it affects the choice of steel for magnets of the dimensions commonly met with in electric supply meters, industrial measuring instruments, magneto generators, and other apparatus requiring magnetic energy in considerable quantity. Such magnets as these are large enough to be made either by casting them or by forging them from rolled bar; magnets which are too small to be made in those ways fall into a different class and will be considered separately.

In making a magnet either by forging it or by casting it, the various operations are the same whatever kind of steel is used, and consequently the only difference in cost between magnets made of different kinds of steel lies in the cost of the steel itself—the raw material.

The three steels which are suitable for permanent magnets differ greatly in price per pound, but in this instance, as in so many other manufacturing problems, to buy the cheapest (the business man's rule of life) is not the way to economy. Magnet steels differ not only in cost but also in the amount of magnetic energy they can maintain, and, other things being the same, the steel to choose is the one which gives the required energy at the lowest cost. Both factors must be taken into account in making a choice between one kind of steel and another, and it will, therefore, be convenient to embody them in a formula.

Let the total quantity of magnetic energy which a magnet is required to maintain in external space be denoted by E. That is to say, let E stand for the useful energy plus the energy in the leakage field. Let e denote the maximum available energy per cm³, which can be maintained by the particular kind of steel it is proposed to use; then the volume of steel for an economic magnet will be E/e cm³. Multiplying by the density d, and dividing by 453·6, gives the weight of the magnet in pounds, and, denoting the price of the steel by p, the cost of the steel for the magnet will be :—

$$\text{Cost of steel for energy } E = \frac{E}{e} \cdot \frac{d}{453 \cdot 6} p$$

In the previous paper it was shown that in a magnet the maximum available energy per cm³ of magnetized steel, when stated in terms of flux and potential difference, is numerically equal to the maximum product of co-ordinates of the demagnetization curve obtained from a closed ring of the same steel after complete magnetization.* Hence, assuming that a demagnetization curve of the steel has been obtained, the quantity e is known. It should be noticed that since E and e appear in the formula as a ratio, these quantities may be expressed either in ergs or in units of flux and potential difference.

The cost formula makes it easy to compare the relative values of different magnet steels, and as an example of the use of the formula a comparison of this kind is given in Table 9 for the three kinds of magnet steel in use at the present time. The tabular figures for the available energy e were obtained in each case from specimens selected for the purpose as being the best of their kind. The carbon steel is an excellent brand of pure carbon tool steel and, although it is not sold as magnet steel, the available energy is unusually high for carbon steel. The tungsten steel is of the standard composition and the figure for available energy was obtained from a length of rolled bar which happened to be almost unspoiled. The cobalt steel was received from the steelworks in a badly spoiled condition, the maximum available energy being only 23 800 ergs per cm³. The piece of steel from which the necessary demagnetization curve was obtained was first submitted to the restoration process, referred to in Part III as applied to tungsten steel. After this heat treatment the available energy was found to be 30 300 ergs, an improvement of 27 per cent. This is the highest value the author has so far obtained from any cobalt steel; and the figure 30 300 ergs has been used as the basis for the tabular figures of cost on the assumption that it is possible for the steelmaker to supply this steel in an unspoiled state. If, however, the spoiled condition in which the steel was supplied represents the best the steelworks can do, then 27 per cent must be added to the tabular figures for the cost of cobalt steel.

TABLE 9.

Description of Magnet Steel	e Energy per cm³	$\frac{E}{e}$ volume of steel	Density of the steel	Weight of steel in one magnet	Price of steel per lb.	Cost of the steel	
						1 magnet	1 000 magnets
	ergs	cm³		lb.	d.	d.	£
Tungsten ..	14 000	107	8·17	1·93	13	25	105
Carbon ..	7 170	210	7·82	3·62	11	40	166
Cobalt ..	30 300	49·5	8·27	0·90	90	81	337

Comparative cost of permanent magnets of equal power, made of Carbon steel, Tungsten steel, and Cobalt steel. E is assumed to be 1 500 000 ergs.

A glance at the cost table shows what an immense advantage tungsten steel has over the other two from the economic point of view. If the only question is how to provide any piece of apparatus with the magnetic energy it needs at the lowest cost, then the choice necessarily falls on tungsten steel. Carbon steel is 62 per cent more costly. Cobalt steel if unspoiled will cost three times as much as tungsten steel; and if it is spoiled it will cost more than four times as much. The disparity may be stated in another way. To bring the other two steels down to the same level of economy as tunsten steel costing 13d. per lb., the price of carbon steel must be reduced to 7d. per lb.; unspoiled cobalt steel to 28d. per lb., spoiled cobalt steel to 22d. per lb.

Turning now to the technical advantages of one steel over another, it is clear from the figures in the cost table that carbon steel is inferior to tungsten steel in cost, in volume and in weight. It is also evident that any advantage which cobalt steel may possess over tungsten steel will have to be paid for by an increase in the cost of steel for any given magnetic requirement. The cost table shows that of two magnets of the

* *Journal I.E.E.*, 1920, vol. 58, p. 798.

same magnetic output, one made of tungsten steel and the other of cobalt steel, the latter will occupy less than half the space. The cobalt steel referred to in the cost table has nearly three times the potency of tungsten steel and consequently the length of the cobalt steel magnet will be about one-third that of the other magnet, provided both are designed for maximum economy. In some circumstances the reduction in length would be a valuable feature. For example, it sometimes happens that the size of the box in which some piece of apparatus is enclosed is governed by the length of the magnet, and in such cases the additional cost of the cobalt steel magnet may be outweighed by a saving in the cost of the box. Again, in portable apparatus the lighter weight of the cobalt steel magnet is in its favour; but whether the saving in weight is worth the additional cost will depend on who carries the apparatus.

Although no one who has mastered the principle of magnetic economy, established in the previous paper, can be under any illusion, the idea is still widely prevalent that cobalt steel necessarily makes a more powerful magnet than tungsten steel. It cannot be too often repeated that if a permanent magnetic field of any given strength is required in any given space, it can always be supplied by a magnet made of any kind of steel which is magnetic. But different steels will result in magnets of very different size and cost, although they will one and all fulfil the given requirement. A cobalt steel magnet will be smaller than the tungsten steel magnet but it will cost more than twice as much, the two magnets being exactly equal in their useful magnetic power. Each will be capable of supplying the required magnetic field, neither more nor less.

However, the small size of the cobalt steel magnet is not the only point in its favour to be set off against the very high cost of the steel. Cobalt steel has another advantage—its unrivalled ability to withstand demagnetizing forces. Taking the simplest possible case for comparison, that of two bar magnets, one of tungsten steel the other of cobalt steel, both temporarily subjected to an adverse stray magnetic field of 20 units, the effect would be a permanent loss of strength amounting to about 14 per cent in the case of the tungsten steel magnet compared with rather less than 3 per cent in the cobalt steel magnet, an advantage of roughly 5 to 1 in favour of cobalt steel. Magnets which are bent so as to form a more or less closed magnetic circuit do not admit of so simple a comparison, but if two magnets of the same shape are subjected to a demagnetizing field, the cobalt steel magnet will have the same relative advantage over tungsten steel as regards loss of strength arising from the action of stray magnetic fields. Whether the advantage is worth the extra cost of cobalt steel will depend on the conditions of use. In many applications of permanent magnetism the magnet never comes under the influence of extraneous magnetic fields in excess of two or three units at the most, and when that is the case a tungsten steel magnet which has been properly treated for stability is just as good as one of cobalt steel, so far as stray fields are concerned.

The permanent magnets of ignition magnetos, and other magneto generators, are liable to be greatly reduced in strength by the action of the armature current. In this example of demagnetization cobalt steel has but little advantage over tungsten steel if both magnets have been designed for economy of steel. But if magnetic economy is entirely disregarded, the substitution of tungsten steel magnets by magnets of the same size and shape made of cobalt steel will be advantageous as regards demagnetization. But in this simple replacement the advantage is only gained at an extra cost far in excess of the relative figures indicated in the cost table.

In considering the pros and cons of cobalt magnet steel it must always be borne in mind that at present prices, and for any given magnetic power, tungsten steel is by far the cheaper steel. To bring the two steels to the same level of cost their prices must be in the same proportion as their maximum available magnetic energy, namely 14 100 to 30 000, a ratio of $2 \cdot 2$. In other words, if two magnets, one of cobalt steel and the other of tungsten steel, are to do the same useful magnetic work at the same cost for steel, then the price per pound for cobalt steel of the best quality must not be more than $2 \cdot 2$ times the price of tungsten steel.

Considerations of economy which govern the design and material of magnets of large size do not apply with the same force to small magnets which lend themselves by their size and shape to being stamped out of sheet steel or cut to length from drawn rod or wire. In magnets which are formed by such means as these, magnetic economy is outweighed by cost of production from the raw material, and some sacrifice must be made in order to use steel of a composition which makes it suitable for the operations of stamping or drawing. Production by stamping from sheet steel necessarily involves a considerable waste of metal in addition to the sacrifice of magnetic power, but in some cases the loss may be justified by the saving in manufacturing cost.

(21) The Optimum Composition of Tungsten Magnet Steel. The Alien Elements.

It has been demonstrated in the last section that, on the score of economy, tungsten magnet steel has no rival at the present time. It will now be shown that the best composition of this steel, far from being a matter of guesswork, is a problem capable of being solved once for all by methodical experiment.

It has been known for a generation or more that tungsten steel makes a better magnet than carbon steel, and anyone would think there had been ample time to discover the best proportions of tungsten and carbon, more than time enough if the problem had been attacked systematically. But that was not to be. In the past, those who had to do with the making of the steel and the magnets being, above all, practical men, their habits of thought were naturally averse to anything resembling orderly scientific method. It was inevitable that accustomed ways should be continued in the hope of finding the best mixture by trial and error. No one knowing what to aim at, progress was slow and crab-like, more especially as one greatly disturbing factor, the degradation of magnet steel by decomposition, was left out of account. With no better guide than random

experiment, the proportions of carbon and tungsten have naturally varied over a wide range. Carbon content has ranged from less than 0·5 per cent to as much as 1·0 per cent, and the tungsten from 3 per cent to 10 per cent or more. But, however slow it might be, the general movement was towards mixtures which at all events showed some approach to finality, and some twelve or more years since at least one German steelmaker was making magnet steel containing 0·70 per cent of carbon and 5 per cent of tungsten, proportions not very far from the best composition. To-day the consensus of opinion among steelmakers would probably put the carbon somewhere between 0·6 and 0·7 per cent and the tungsten at about 6 per cent. To this point, then, trial and error have managed to bring us in the course of 30 or 40 years, entirely unaided by knowledge of the factors which govern the magnetic energy maintained by magnet steel. Like all improvements founded on the same primitive methods, the advance has only been made at excessive cost in time and money. With the better knowledge of the relation between steel and permanent magnetism that is now available, it is possible to determine the best composition of any kind of magnet steel from first principles. Taking the maximum useful magnetic energy per unit volume of steel as the criterion, the necessary data can be obtained from the demagnetization curves of a number of specimens of steel in which the proportions of the several constituents are varied in suitable gradations.

For the determination of the best composition for tungsten magnet steel the necessary experimental data have already been obtained, mainly in the course of the author's investigation of the relation between carbon content and coercive force in steel containing 6 per cent of tungsten. The maximum available energy was ascertained experimentally for each of the samples of steel used in the preparation of the carbon-coercive-force curve given in Fig. 9. On plotting carbon content and available energy as co-ordinates a curve was obtained showing a steady increase of energy with increasing carbon, rising to a maximum for a carbon content of about 0·73 per cent. Beyond this point the energy gradually decreased, the curve being traced up to a carbon content of 1·3 per cent. But this preliminary determination of the most favourable carbon content was made before the discovery of the deficiency of Alpha iron in ultraheated tungsten steel. After the investigation of ultraheated steel it became clear that if any of the specimens used in determining the available energy happened to be in the ultraheated state when under test, the value of the energy computed from the observational data would be less than the maximum which the steel would be capable of maintaining if all the iron were in the Alpha state. But a deficiency in Alpha iron only affects one of the factors of magnetic energy, namely the flux. The other factor, arising indirectly from the potency of the steel, would be unaffected; since ultraheated tungsten steel when hardened has all the carbon in solution, and consequently the steel would have the full potency corresponding with the carbon content. Hence the possibly ultraheated condition of the test-pieces would affect neither the accuracy of the carbon-coercive-force curve nor the accuracy of the preliminary figure obtained for the best carbon content, namely 0·73 per cent. But by reducing the flux factor, ultraheating would result in a lower value for the energy corresponding with any given carbon content. These considerations led the author to make a careful scrutiny of all the available experimental records in order to utilize only those experiments in which the heating which the steel had undergone, before the hardening, had been sufficient to convert all the iron into the Alpha state. The energy values which survived this examination are plotted in Fig. 27. The three test-points indicated by crosses relate to three test-pieces which are not on quite the same footing as the others, the record in their case being incomplete, but so far as they go these three test-points confirm the general course of the curve.

It need hardly be said that in seeking to determine the best the steel can do, the presumption is always

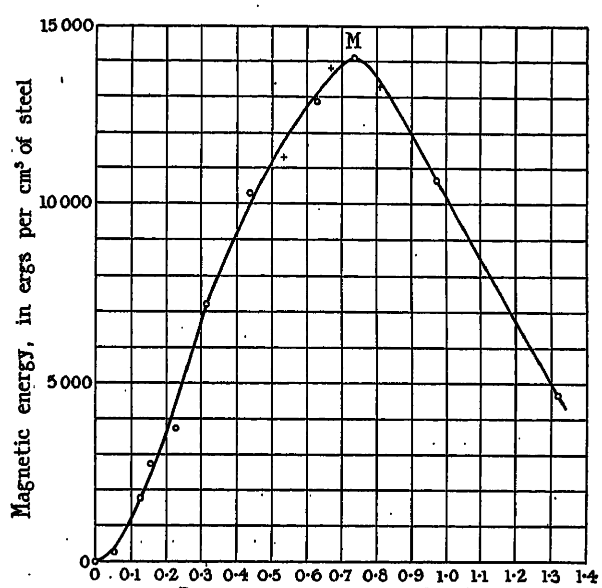

FIG. 27.—Available magnetic energy of hardened tungsten magnet steel containing 6 per cent of tungsten. Curve showing the relation between the carbon content and the available energy in ergs per cm³ of steel.

in favour of the highest observed values, subject, of course, to errors of observation. Lower values are always apt to occur from those accidental deficiencies of one kind and another to which magnet steel is only too liable. The point plotted at M deserves particular attention. It was determined from two test-pieces of 6 per cent tungsten steel used in the course of the experiments on the spoiling and restoration of magnet steel. Two pieces were cut from a length of rolled bar which had been selected for experimental use by reason of its quite exceptional uniformity in carbon content. Part of each piece was made into an ellipsoidal test-piece for the magnetometer, and the remainder submitted to chemical analysis. The demagnetization curves obtained from the two ellipsoids were indistinguishable from one another. The carbon content of the two specimens proved on analysis to be 0·735 and 0·736 per cent. In the author's experience of experimental work of this

nature, such uniformity as this is very seldom realized. It is merely a fortunate chance that the two specimens of steel happen to give an energy value closely approaching, if not actually coinciding with, the maximum ordinate of the curve in Fig. 27, and that this particular point should have been determined with exceptional precision.

The curve given in Fig. 27 expresses the law governing available energy and carbon content in 6 per cent tungsten steel, as closely as existing observational data can determine it. In the nature of things the highest point of a rounded curve such as this cannot be sharply defined, but the most favourable carbon content is certainly above 0·70 and below 0·76 per cent. It will be near enough to take the mean value, 0·73 per cent, as the optimum carbon content.

Having determined the total quantity of carbon, attention must next be directed to the proportion in which the total should be divided between the two carbides WC and Fe_3C. All the specimens of steel used in determining the maximum energy contained 6 per cent of tungsten. Hence when the steel contains the optimum proportion of carbon, namely 0·73 per cent, carbide of tungsten will utilize $6 \times 12/184$, or 0·39, leaving 0·34 to form carbide of iron. That is to say, out of a total of 73 molecules, each containing an atom of carbon, 39 molecules will be tungsten carbide and 34 will be carbide of iron. As matters stand, therefore, there is a rough equality in the number of the two kinds of potency-giving molecule. For some reason or other there is always a presumption (real or imagined) in favour of equality, and in the present case the suggestion receives support from the carbon-coercive-force curve given in Fig. 9. Examination of the two portions of the curve shows that for a carbon content of 0·73 per cent, the upper curve S2, which relates to the molecule Fe_3C, has a greater slope than the lower curve S1 at the corresponding point, namely carbon 0·39 per cent. Hence if, without changing the total carbon content, a little carbon were to be transferred from the tungsten carbide to the carbide of iron the increment of coercive force arising from Fe_3C would be greater than the decrement in the coercive force produced by the tungsten carbide, and the transfer would increase the potency of the steel. Assuming for the moment that the shape of the upper curve S2 is not affected in any way by the transference of carbon, it is easy to trace the increase in coercive force by measuring successive increments and decrements on the curves S2 and S1. The figures given in Table 10 have been arrived at in this way and it will be seen that according to the tabular figures a tungsten content of 5·2 per cent would yield the highest coercive force. But it is certain that the transfer of carbon from one carbide to the other would gradually change the shape of the curve S2. To what extent the change would affect the figures in Table 10 cannot be determined, but a comparison of the upper portion of the curve in Fig. 9 with Mme. Curie's curve for carbon steel (Fig. 8), shows that the alteration in the shape of S2 will be in the direction of a diminished slope. Now with a diminished slope it is certain that the highest coercive force would be given by a tungsten content greater than 5·2 per cent, and consequently the most favourable tungsten content must be somewhere between 5·2 and 6·0 per cent. Nearer than this it is not possible to go at the present time, and knowing no better we shall again take the average figure, putting the optimum tungsten content at 5·6 per cent. With this percentage of tungsten the carbon in the form of tungsten carbide will be $5 \cdot 6 \times 12/184$, which is 0·365 per cent. This, as it turns out, is exactly half the total amount of carbon, 0·730 per cent, and since the remainder of the carbon forms carbide of iron we shall have the number of molecules of Fe_3C exactly equal to the number of molecules of tungsten carbide. Hence, so far as it is possible to judge from the carbon-coercive-force curve, a total carbon content of 0·73 per cent will yield the maximum potency when one-half of it is in the form of tungsten carbide and the other half is carbide of iron.

TABLE 10.

Carbon as Fe_3C	Carbon as WC	Tungsten	Coercive force: Derived from Fe_3C	Coercive force: Derived from WC	Coercive force: Total
0·33	0·39	6·00	25·3	45·0	70·3
0·34	0·38	5·85	26·1	44·7	70·8
0·35	0·37	5·69	26·9	44·3	71·2
0·36	0·36	5·54	27·4	44·0	71·4
0·37	0·35	5·38	28·1	43·4	71·5
0·38	0·34	5·22*	28·9	42·9	71·8*
0·39	0·33	5·08	29·5	42·2	71·7
0·40	0·32	4·92	30·0	41·6	71·6
0·41	0·31	4·77	30·6	40·6	71·2
0·42	0·30	4·61	31·1	39·9	71·0
0·43	0·29	4·46	31·6	38·9	70·5
0·44	0·28	4·31	32·0	37·8	69·8

Tungsten steel containing 0·72 per cent of carbon. Computed variation in total coercive force with varying content of tungsten, showing a maximum potency with 5·2 per cent of tungsten.

* Maximum.

It should be noticed that a change in the way in which the total carbon is divided between the two carbides only affects one of the factors of magnetic energy, namely, that arising indirectly from the potency, and hence the apportionment which yields the highest potency must necessarily give the maximum available energy. The presumption in favour of equality of the two carbides is therefore justified by the facts so far as they are known.

Having ascertained the most favourable percentage for the total amount of carbon, and noted that equality of the two carbides gives the maximum energy, the optimum composition of tungsten magnet steel is settled. For easy reference the composition is set out

in Table 11 both in percentage quantities and in proportional numbers of molecules.

In every analysis of steel a number of alien elements force themselves on our attention, their prominence being out of all proportion to the quantities in which they occur. The aliens commonly present in magnet steel are sulphur, phosphorus, arsenic, silicon and manganese; but occasionally copper, nickel and chromium occur. The total quantity of alien elements found by analysis in a number of batches of tungsten magnet steel, supplied by different steelmakers, has amounted on an average to 0·53 per cent of the weight of steel; the smallest amount in any lot of steel being 0·29 per cent and the largest 0·75 per cent.

Among the aliens, sulphur, phosphorus and perhaps some others, are believed to be detrimental to the

TABLE 11.

Composition by Analysis.	
Element	Percentage weight
Iron	93·00
Tungsten	5·60
Carbon	0·73
Aliens (allowance)	0·67
Total	100·00
Molecular Composition.	
Solvent iron (diatomic)	1 000
Carbide of tungsten, WC ..	39
Carbide of iron, Fe_3C	39
Aliens (allowance)	22

Optimum composition of tungsten magnet steel (author).

mechanical strength of steel, but it is unlikely that any of the aliens, with the exception of manganese and chromium, have an appreciable effect on magnetic properties. If the aliens were not there, a little more space would be available for iron and to that extent their absence would be beneficial. Manganese in excess is unwelcome in a permanent magnet. This element is added to steel in order to counteract the injurious influence of sulphur on mechanical strength, the manganese combining with the sulphur to form an innocuous sulphide. But in magnet steel there is always a good deal more manganese than is necessary for this purpose, and it is to the surplus that suspicion attaches. Manganese is known to form a non-magnetic compound with iron, and the surplus quantity in magnet steel is often enough to rob the magnetic mechanism of its magnetic molecules to the extent of 3 or 4 per cent. On this account, it is desirable to limit the percentage of manganese to an amount which will serve the intended purpose without leaving more than a small excess.

Chromium needs a paragraph to itself. The great potency-giving power of carbide of chromium, and the loss of magnetism in steel containing chromium, have already been referred to in Section (6). The very high coercive force imparted to steel by chromium was discovered many years ago by Mme. Curie, who at the same time was aware of the harmful effect of chromium in magnet steel. But this knowledge has not, even yet, found its way into every steelworks. Now and again, at intervals of a few years, steel containing chromium is introduced as a newly-discovered magnet steel, stress being laid on high coercive force. But the deficiency of inherent magnetism, which invariably outweighs the gain in potency, is either overlooked or at all events passed over in silence. There can hardly be a doubt that the deficiency in Alpha iron is the result of ultraheating, just as it is in the case of tungsten steel, and it may be assumed that the harmful effect of chromium could be removed by suitable heat treatment. But judging from the behaviour of high-speed tool steels, the ultraheated condition, once acquired, is retained with extraordinary persistence when the steel contains chromium, and until a practicable remedy is forthcoming for deficiency in the inherent magnetism, chromium even in very small quantities should be avoided both in tungsten steel and carbon steel. So far the only serviceable remedy has been the introduction of another magnetic element, namely cobalt. But even this seems only a partial remedy, a considerable deficiency in magnetism being a common fault in cobalt magnet steel.

The great potency-giving power of carbon combined with chromium is naturally an alluring fact, but it seems incumbent on those who wish to exploit it that they should begin by making a thorough investigation of the action of chromium, with a view to annulling its harmful influence on magnet steel.

(22) THE CONDITION OF ROLLED MAGNET STEEL AS IT COMES FROM THE STEELWORKS.

Bars of rolled magnet steel are, for the most part, badly spoiled. They are also in the fully ultraheated condition. These statements apply both to tungsten steel and cobalt steel.

It will be convenient to attend first to the effect of ultraheating and to consider the practical steps to be taken for bringing the steel into the normal or all-Alpha state required for a good magnet. The abnormal condition of rolled magnet steel as the magnet maker receives it is illustrated by the three demagnetization curves given in Fig. 28. These curves were obtained one after another from a test-piece made from a bar of ordinary rolled magnet steel, containing 5 per cent of tungsten and 0·70 per cent of carbon. The first curve, A, was obtained when the steel was in the condition in which it was received from the rolling mill. The second curve, B, was obtained after hardening the test-piece. The third curve, C, was obtained after softening the hardened test-piece by heating it to 700° C, keeping it

at that temperature for two minutes, and then allowing it to cool in the open air to room temperature.*

A moment's consideration will show that curve A cannot represent magnet steel in a normal condition. Iron and steel are rolled at a bright red heat and after the operation the rolled bars are allowed to cool down slowly. As the temperature of the metal falls slowly through the region between 700° and 600° C. there is ample time for the whole of the surplus carbide to pass from solution to crystal, and hence if the steel after being rolled were in the normal state it would give a demagnetization curve like curve C, in which the coercive force is rather less than 18. But in fact the steel as it came from the rolling mill had a coercive force of 29, or 11 units greater than the value for the softened piece.

The phenomena of ultraheating are described at length in the Appendix, where it is shown that in

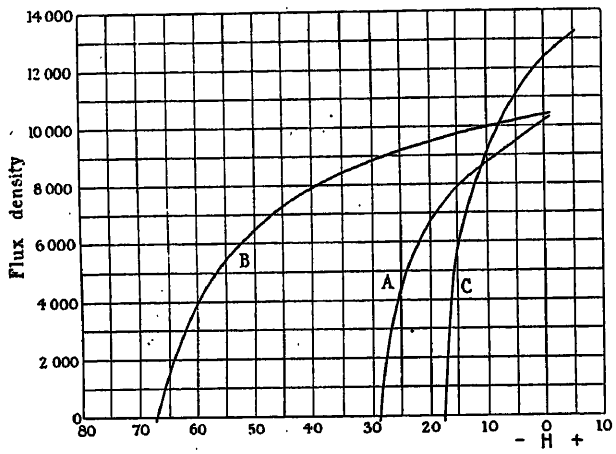

FIG. 28.—Demagnetization curves obtained from tungsten magnet steel in different states:—

Curve A, the steel in the softened state as received from the steelworks; illustrating the effect of ultraheating.
Curve B, the steel after being hardened.
Curve C, after softening the hardened steel.

tungsten magnet steel which has cooled down slowly enough to permit all the surplus carbide to pass out of solution, a coercive force so high as 29 units is a clear indication that the steel is in the fully ultraheated condition. Now the rate at which a bar of steel cools down after the rolling gives ample time for the whole of the surplus carbon to pass from solution to crystal, and consequently the piece of rolled steel from which curve A was obtained must have been in the fully ultraheated state. In the author's experience this is invariably the case with rolled magnet steel as it comes from the steelworks.

Two methods of heat treatment for curing ultraheated tungsten magnet steel are described in the Appendix. It can be done by prolonged heating at about 700° C.; or as an alternative the steel can be cured in two operations, each consisting of heating to about 750° C. and then immediately allowing the steel to cool down slowly. The latter plan is the more convenient in practice, because of the two heats which are necessary for a complete cure, one is performed incidentally in the course of forging or bending the magnets to the required shape.

Assuming that the forging or bending heat is relied on to complete the cure, the first curing heat may be performed as follows. After cutting up the rolled bars into pieces of the required length for making magnets, a number of pieces may be packed together inside a furnace and heated. As soon as the temperature of the steel has risen to 750° C., the supply of heat should be cut off and the furnace, with the steel inside it, allowed to cool down. Under these conditions the temperature of the steel will fall through the region favourable to curing, that is to say from 750° C. to about 600° C., slowly enough to remove about two-thirds of the whole effect of ultraheating. In other words, the amount of Gamma iron present in fully ultraheated 6 per cent tungsten steel will be reduced from 16 per cent to about 6 per cent.

An incidental result of this first operation for the cure of ultraheating may be noticed in passing. In the course of the operation, the temperature of the steel will be in the neighbourhood of 700° C. for some minutes. There will, therefore, be ample time for surplus carbide to pass out of solution, and consequently at the conclusion of the operation the pieces of steel will be soft and easy to machine.

For the purpose of forging or bending the pieces of steel to the required shape, they will subsequently be heated to about 900° C. At the conclusion of the process they must be allowed to cool down slowly in the ordinary way. By this means the steel will, for the second time, pass slowly through the temperature region favourable to curing and the remainder of the ultraheating effect will be removed, leaving the steel in the normal or all-Alpha state.

The preliminary heat may perhaps be regarded as an unnecessary refinement. If it is omitted, however, the slow cooling after forging will be the only opportunity given to the ultraheated steel to return to the normal state, and out of the 16 per cent of Gamma iron not more than 9 or 10 per cent can be counted on with certainty to change into the Alpha variety. Hence the steel will be likely to contain at least 6 per cent of Gamma iron and consequently the finished magnet will be 6 per cent weaker than it need be.

Turning now to the consideration of the spoiled condition in which magnet steel comes from the steelworks, it must be borne in mind from the outset that, unlike ultraheating which is a curable disease, spoiling cannot be cured effectively after the steel has been rolled down into bars. So far as the magnet maker is concerned, spoiling is an incurable disease, present in nearly all the magnet steel he buys.

Ultraheating and spoiling affect the two properties which give rise respectively to the two factors of the useful energy which a magnet is intended to maintain. Ultraheating adversely affects the inherent magnetism of the steel, spoiling injures the potency. The extent

* The reader who associates softening with the vague word annealing, easily imagines it to be a lengthy operation possibly involving slow cooling over many hours. It is, however, an affair of a few minutes when it takes place within the region of temperature just below the boundary where Beta is transformed into Alpha iron. Here the steel is still red hot and the molecular mobility so great that the whole of the surplus carbide will pass out of solution in a couple of minutes, leaving the steel quite soft. Given that brief time, slow cooling thereafter is needless, and the steel might then be dropped into cold water; it would be just as soft.

of the injury caused by spoiling varies over a wide range, the variation being much the same in every batch of rolled magnet steel. In this respect there is nothing to choose between the product of one steelmaker and another. All are alike, the uniformity of mischief pointing to a common practice in the heat treatment which the steel receives in course of manufacture. An example of the product of one steelworks will fairly represent them all, and for the purpose of illustration we shall choose a batch of tungsten steel which, in composition, closely approached the optimum proportions, the average of three analyses showing that

TABLE 12.

Group	Number of lengths of rolled bar	Coercive force	Deficiency (units)	Available energy, ergs per cm³
	0	71	0	14 000
a	1	70	1	13 800
b	0	69	2	13 700
c	2	68	3	13 500
d	4	67	4	13 300
e	9	66	5	13 150
f	17	65	6	13 000
g	26	64	7	12 800
h	32	63	8	12 600
i	37	62	9	12 420
j	29	61	10	12 250
k	19	60	11	12 070
l	11	59	12	11 900
m	7	58	13	11 720
n	3	57	14	11 550
o	4	56	15	11 370
p	0	55	16	11 200
q	0	54	17	11 000
r	1	53	18	10 800
	202 lengths of steel in the batch.			

Spoiled condition of a typical batch of rolled tungsten magnet steel. The 202 lengths of steel in the batch are classified according to coercive force.

the steel contained 6·05 per cent of tungsten and 0·732 per cent of carbon. With the aid of the carbon-coercive-force curve given in Fig. 9, it is easy to show that when steel of this composition is in the hardened state it should have a coercive force of 71·0, provided it is unspoiled.

The batch of steel was supplied in 202 lengths rolled to a rectangular section 1 in. wide and $\frac{3}{8}$ in. thick. In accordance with the usual routine, two samples cut from each length were hardened and tested for coercive force in order to gauge the extent of degradation by spoiling. The mean value of the coercive force of a pair of samples was taken as the coercive force of the corresponding length of rolled bar. The tests are classified in Table 12, where the 202 lengths are sorted out into groups according to their coercive force, all the observed values for the different lengths in any group being within half a unit either way of the tabular figure.

It will be seen that the coercive force of this batch of steel varied from a maximum of 70 to a minimum of 53, the degradation arising from the spoiling which the steel had undergone in course of manufacture, varying from 1 unit at the best to 18 units at the worst. Precise figures for the corresponding loss of magnetic energy are not so easily obtained. They could only be arrived at by the laborious method of tracing a demagnetization curve for every length of steel in the batch. It can be shown, however, that for any given flux density the falling off in energy as the result of spoiling is nearly proportional to the falling off in coercive force. Hence with the aid of two demagnetization curves, one for unspoiled steel and the other for the same steel badly spoiled, the energy loss for any degree of spoiling which falls between the two curves can be estimated with sufficient accuracy by a method of interpolation. In the present case the demagnetization curves given in Fig. 16 are available, since they relate to the particular batch of steel we are now considering. By interpolation between curve 1 and curve 2, values have been computed for the maximum available energy of the steel in each group of lengths in the batch, and the computed figures have been inserted in Table 12. The energy of the 202 lengths of steel in the condition in which they were received from the steelworks varied from 13 800 ergs in the least spoiled length to 10 800 ergs in the most badly spoiled piece. In terms of available magnetic energy the mean degradation of the batch is a little over 11 per cent, and at the worst it is 23 per cent.

The figures given in Table 12 show how great is the need for radical improvement in the manufacture of magnet steel. Apart from the one or two lengths of really good tungsten magnet steel which sometimes occur, apparently by accident, unspoiled magnet steel, as a regular product, is unknown.* In place of it the magnet maker receives a strange assortment of more or less decomposed steel. What is he to do with it? If he designs his magnets on the basis of the available energy of the least badly spoiled steel in the batch, then the magnets in bulk will fail to meet his requirement. On the other hand, if the worst steel in the batch is taken as the basis of design, then the bulk of the magnets will contain a greater volume of steel than they need, an excess which has to be paid for.

An example with money in it will drive the point home. Suppose some piece of apparatus is to be made in considerable numbers. To fix our ideas we may suppose a thousand of them are to be made at one time, and that each requires a permanent magnetic field of 2 000 in an air space 10 cm² in area, and 0·5 cm in length measured along the lines of force. With these dimensions and strength of field, the magnetic energy maintained in the air space will be 796 000 ergs and, allowing for an equal amount in the leakage field, the total requirement will be 1 590 000 ergs. We may suppose that the permanent magnet which is to provide this energy is to be made of tungsten magnet steel like that classified in Table 12, and that the length of steel at the bottom of

* Up to the present time, the author has not come across a single piece of cobalt magnet steel that was not badly spoiled.

the list has been returned to the steelmaker as useless. The magnet must now be designed either on the basis of the best length in the batch which gives 13 800 ergs per cm^3, or on that of the worst remaining lengths, namely those in group (o), which give 11 370 ergs per cm^3. In the first case the volume of the magnet will be 1 590 000/13 800, and in the second case 1 590 000/11 370. At the best, therefore, the volume of the magnet will be 115 cm^3 and at the worst 140 cm^3, the corresponding weights being 2·07 lb. and 2·52 lb. One thousand of these magnets will be required and, allowing 10 per cent for the wastage of steel in cutting up and machining, the total quantity of steel will be 2 277 lb. in the first case or 2 772 lb. in the second. A comparison of the cost of 1 000 magnets is given in Table 13, where the price of the steel is that ruling in November 1923, for 6 per cent tungsten steel containing 0·7 per cent of carbon.

It will be seen that to ensure every magnet fulfilling the requirement, the only course open to the magnet maker is to found his design on the most badly spoiled steel in the batch. This involves an increase of 23 per cent in the quantity of steel, and in effect the material for the magnets costs 22 per cent more than it need do. In other words, if the magnets are to do what they are intended to do, the magnet maker is called upon to pay a kind of tax, amounting to between £20 and £30 a ton, for the privilege of using decomposed steel.

TABLE 13.

Condition of steel	Weight of one magnet	Cost of 1 000 magnets
	lb.	£
Spoiled	2·52	150
Unspoiled	2·07	123

Comparative cost of tungsten steel permanent magnets of equal power, made of spoiled steel and unspoiled steel.

It is desirable to find a remedy for this state of things. In the author's opinion a complete remedy is well within the bounds of possibility and, although it is the business of the steelmaker to make unspoiled magnet steel it may be useful to state briefly what are the grounds for believing it to be possible to produce rolled magnet steel in the unspoiled or restored state. But first to clear the air. Nothing is to be gained by ringing the changes on the ingredients. For so long as the potency of magnet steel is derived from molecules which, like the carbides of iron and tungsten, suffer decomposition in Gamma iron, it is surely obvious that no modification in the proportions of the constituents of the steel can have any material effect on the spoiling. The warning is called for because already one enterprising steelmaker has tried to cure the disease by changing the proportions of the solute molecules. His plan was to reduce the quantity of carbon. The argument seems to have been that since unstable carbide molecules are the origin of the mischief the fewer there are of them the better. Accordingly some of them were left out and to make up the depleted coercive force a little chromium was added. The result might have been anticipated. There was no improvement; on the contrary, the deficiency in carbon and the presence of chromium reduced the available magnetic energy in the entire batch of steel, but left the disease of spoiling untouched. In short, the attempt at improvement, however well intentioned, was misconceived; a plum pudding cannot be improved by leaving out some of the plums. Research may one day discover a new potency-giving molecule of a more stable kind; one that does not suffer any decomposition at the temperatures usually attained in making magnet steel. That would, of course, entirely remove the source of degradation by spoiling, but a remedy will never be found by tinkering with the proportions of the known constituents of magnet steel.

Pending the possible discovery of a perfectly stable molecule of the potency-giving kind, we have to make the best of the magnet steels already known, and the problem for the steelmaker is to modify the heat treatment of the steel in such a way that the rolled bars are turned out in the unspoiled or restored state. In both tungsten steel and cobalt steel slow decomposition is inevitable in course of manufacture because it is impossible to avoid the danger zone of temperature. But at any temperature above the upper boundary of the danger zone, recombination is equally certain and in that fact lies the true remedy for spoiled steel.

The author's investigations have been mainly concerned with tungsten steel. Cobalt steel behaves in much the same way both as regards spoiling and restoration, but the limits of the danger zone of temperature have not been determined. In what follows, therefore, attention will be confined to tungsten steel. The temperatures referred to will be those measured in the course of the author's experiments; they are probably true for any ordinary tungsten magnet steel within about 5 degrees either way.

It has been shown in Section (13) that the boundary where spoiling ceases occurs at about 1 214° C.; and that at 1 240° C. restoration proceeds with such rapidity that very badly spoiled steel would be completely restored in the course of two or three minutes. Hence if every piece of steel, before being rolled, were to be heated to 1 240° C. for a few minutes the problem of spoiled steel would be solved. For the steel would be restored before it was rolled and in place of the deplorable range of degradation shown in Table 12 we should have every length of steel in the batch as good as the best, all equally unspoiled.

It is for the steelmaker to find out how to carry out the restoring operation in practice. Difficulties will naturally be encountered but none are likely to be insuperable. High temperatures are in themselves a difficulty, but it is an encouraging fact that the temperatures already attained in ordinary practice are not very far below the restoring temperature. This we may easily see without prying into the secrets of the steelworks, because every length of magnet steel which comes from the rolling mill has the outline of its thermal history written at large all over it in magnetic characters.

By way of example we may consider the history of some of the lengths of steel classified in Table 12, choosing those in group (i) as representing the average of the whole batch of steel so far as spoiling is concerned. Since the lengths in this group are badly spoiled they must necessarily have been within the danger zone (between 750° and 1 214° C.) for some considerable time. But in common with all rolled tungsten magnet steel this batch of steel was in the fully ultraheated state and consequently it must have attained a temperature above 1 073° C., the ultraheating boundary. Hence the temperature of the steel preparatory to the operation of rolling must have been somewhere between 1 073° and 1 214° C. It will be sufficient for our present purpose to strike an average between these two figures and say that the temperature to which the steel was raised for the purpose of rolling was about 1 140° C. It will be observed that this is no more than 100 degrees below the temperature at which the restoration of spoiled steel takes place with great rapidity. Clearly, then, the restoration of the steel does not involve any extraordinary advance in temperature.

It remains to account for the occurrence of a few unspoiled lengths of steel now and again. Molten steel is unspoiled, but the metal cannot remain so from the time it was poured into the ingot mould until it arrived at the rolling mill, because in the interval it has cooled down and then been heated again, thus passing more than once through the danger zone. The steel is therefore necessarily more or less spoiled before it is ready for the rolling. Hence the only possible explanation of the casual production of a few lengths of unspoiled steel must be that occasionally the temperature of the rolling-mill furnace rises above 1 214° C. and sets going the process of restoration. How far restoration will go depends on three factors, namely the extent of spoiling to be made good, the margin of temperature or number of degrees above 1 214° C., and the time afforded for the progress of restoration before the steel is withdrawn from the furnace for rolling. With a small margin of a few degrees only, it might easily happen that the steel was removed from the furnace and rolled before the restoration was complete. With a larger margin, if for example the temperature rose to 1 240° C., complete restoration would be effected in two or three minutes. In this way it seems possible to account for the common occurrence of a few bars of steel very little spoiled, and the occasional production of one or two lengths which show no trace of spoiling; by accident they have been completely restored immediately before they were rolled.

Whatever the precise explanation may be, the fact that unspoiled, or perfectly restored, magnet steel is occasionally produced is conclusive evidence that the temperature of the steel, shortly before rolling, sometimes exceeds 1 214° C.; or to speak more precisely, the temperature rises now and again above the upper boundary of the danger zone and passes into the region in which restoration takes place. The means for producing the restoring temperature are therefore already in existence in every steelworks where magnet steel is made and rolled, and sometimes that temperature is attained. It may be an accident, perhaps an undesirable accident from the steelmaker's point of view. Nevertheless, when that accident is made deliberate and intentional the production of decomposed magnet steel in rolled bars will become a thing of the past. It is not a question of gradual improvement. Below 1 214° C., or whatever the precise temperature turns out to be, things will go on just as they do now. Above 1 214° C. there will be no spoiled steel. It will be improvement *per saltum*, all or none.

In the following section it is shown that permanent magnets can be produced by casting them direct from molten magnet steel, a method which may ultimately oust the traditional rolled steel magnet altogether. The cast magnet has the incidental advantage of being almost entirely unspoiled.

(23) Cast Magnets.

In the previous paper * a distinction was drawn between the customary form of magnet made from rolled steel bar of uniform sectional area, and the ideal form in which the sectional area is gradually diminished from the neutral section, along the magnet limbs, to the polar surfaces; the gradual reduction in area being done in such a way as to secure uniform flux density in the steel. It was pointed out that "magnets of this kind utilize the steel to the best advantage, but until it becomes possible to make permanent magnets in the form of magnet-steel castings, so as to permit the sectional area to be varied appropriately, the magnet of uniform density must be regarded as an ideal type."

Shortly after the publication of that paper, the suggestion that permanent magnets might be cast was taken up by the British Scientific Instrument Research Association, in order to ascertain whether it was possible, with the means already available, to make sound castings in magnet steel of the forms required for permanent magnets; and, if so, whether magnet steel in the cast state was suitable for the purpose. The problem was mainly one for the steel foundry, and the Association had the good fortune to obtain the cooperation of Sir Robert Hadfield, who undertook the preparation of such experimental castings as might be required in the course of research. At the request of the Director of Research, Sir Herbert Jackson, the present writer dealt with the magnetic part of the investigation and, by arrangement, this section of the paper takes the place of a formal Report to the Committee of the Association.

The universal and age-long practice of using rolled steel for permanent magnets has led, not unnaturally, to the idea that in some way or other the rolled state of steel and permanent magnetism go together, almost as cause and effect. It is not easy to rid ourselves of a notion of this kind, even when there is no rational foundation for it. The first step, therefore, was to ascertain what magnetic difference there is, if any, between the rolled and the cast state of magnet steels. For this purpose a few cylindrical rods, of about 1 in. diameter, were cast in tungsten magnet steel for comparison with rolled steel of approximately the same composition, the cast metal containing, by analysis, carbon 0·69 per cent and tungsten 6·1 per cent. The cast rods presented

* *Journal I.E.E.*, 1920, vol. 58, p. 797.

much the same external appearance as ordinary steel castings, the surface being perhaps rather more deeply pitted than usual; but of porosity there was no sign. Having turned off the skin in the lathe and finished the cast rods as true cylinders, their average density, computed from their weight and dimensions, was found to be 7·92. This figure is to be compared with 8·17, which is the density of rolled tungsten steel of the same composition, the difference being 3·1 per cent. On sawing the rods in half lengthways so as to secure a longitudinal section, a small " pipe " was found, extending along the axis for the greater part of the length. The pipe is, of course, the result of the contraction during cooling, and it accounts for most of the difference in density just noticed. Elsewhere the steel was sound, only one or two very small bubbles being visible on the sawn surfaces.

Two magnetometer test-pieces of ellipsoidal form were machined from the sawn cylinders, care being taken

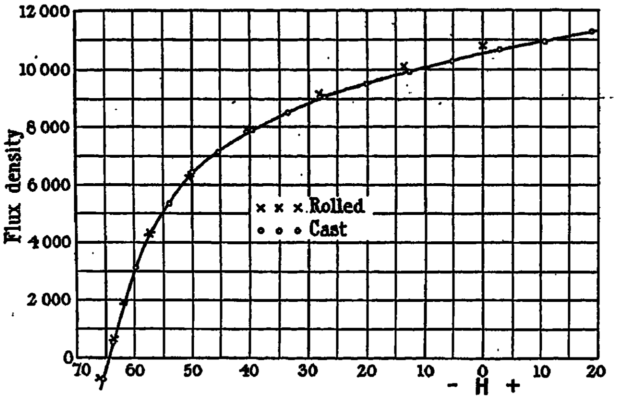

FIG. 29.—Cast tungsten magnet steel. Demagnetization curve obtained from a specimen of the cast steel in the hardened state. The points marked by crosses are taken from a typical specimen of rolled tungsten magnet steel in the hardened state.

to avoid using the steel in the neighbourhood of the pipe. These two test-pieces having been accurately measured and weighed, their densities were found to be 8·081 and 8·134 respectively, the mean value being 8·107, which is less than 1 per cent below the density of the rolled steel.

The test-pieces were next hardened by quenching from a temperature of 850° C. It has been shown in Section (16) that immediately after hardening the coercive force of magnet steel is abnormally high, and it only settles down to a reasonably steady value after several hours. For this reason it is necessary in all work of precision to allow a good many hours to elapse after the hardening before embarking on magnetic tests. In all the investigations described in this paper, including those referred to in the present section, a long interval, on no occasion less than 17 hours, has been allowed for the hardened steel to settle down.

The two hardened test-pieces proved to be so nearly identical in their magnetic properties that the differences between them would be barely perceptible on the scale of the magnetic curves in this paper. A demagnetization curve plotted from the mean values of the observations made on the two test-pieces is given in Fig. 29. For comparison a number of points, marked on the diagram by crosses, have been taken from the demagnetization curve of a specimen of rolled tungsten steel of approximately the same composition as the cast steel, namely about 0·7 per cent of carbon and 6 per cent of tungsten. A quantitative comparison of the rolled and cast specimens is given in Table 14.

The figures in the table show that, of the two test-pieces, the cast steel is slightly inferior to the rolled metal, but the differences are no greater than those frequently met with between two specimens of rolled steel taken from different bars in the same batch, or even from the same bar; and they probably arise from the same cause, namely small variations in the content of carbon. The small differences in the tabular figures dispose at once of the idea that the rolling of magnet steel has any marked influence on magnetic properties. For the purpose of making magnets there is clearly no

TABLE 14.

Magnetic quantity	Rolled steel	Cast steel
Coercive force	64·6	64·4
Remanent flux density ..	10 810	10 550
Economic flux density ..	7 250	7 150
Available M.M.F. per cm at the economic density ..	45·6	45·3
Maximum available energy in ergs per cm³ of steel..	13 150	12 880

Magnetic comparison of cast tungsten magnet steel with rolled steel of the same composition.

material difference between the cast and the rolled state of tungsten magnet steel.

At the suggestion of Sir Robert Hadfield a similar comparison was made between cast and rolled specimens of cobalt magnet steel, the composition chosen for experiment being one which gives a maximum available energy of about 24 000 ergs per cm³ of steel, not far short of double the energy of tungsten magnet steel.

In the case of tungsten steel, magnetic data for the rolled state were already available in abundance and it was unnecessary to make special tests of the rolled metal for the purpose of comparison. But that is far from being the case with cobalt steel, and it was necessary to adopt a different procedure in order to make a strict comparison between the cast and the rolled metal. The method adopted was to melt the required quantity of steel in a crucible and to cast several test rods and a small ingot from the molten metal, thus ensuring uniformity of composition. The cast cylindrical rods were dealt with in precisely the same way as that already described in connection with tungsten steel, two magnetometer test-pieces of standard ellipsoidal form being machined from them. The ingot was cogged and rolled down into a bar of convenient section, from which two similar magnetometer test-pieces were prepared. The four test-pieces were then hardened by quenching them

from 900° C., and a complete demagnetization curve was obtained from each test-piece after the lapse of about 20 hours.

The two curves for the cast metal being very nearly alike, an average curve plotted from the mean ordinates of the pair of curves will fairly represent the magnetic

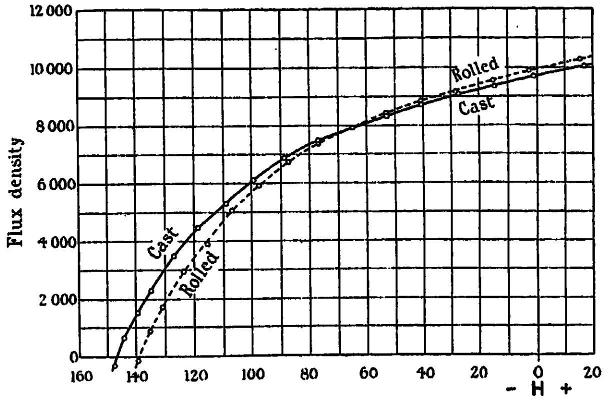

FIG. 30.—Cast cobalt magnet steel. Demagnetization curves obtained from the cast and the rolled steel, in the hardened state.

condition of the cast metal. The same applies to the two curves obtained from the rolled steel specimens. The two average demagnetization curves are shown in Fig. 30, and a quantitative comparison between the rolled and the cast metal is given in Table 15, the figures being derived from the average curves.

TABLE 15.

Magnetic quantity	Rolled steel	Cast steel
Coercive force..	138	147
Remanent flux density ..	9 900	9 650
Economic flux density ..	6 400	6 400
Available M.M.F. per cm at the economic flux density	91·0	94·6
Maximum available energy in ergs per cm³ of steel..	23 200	24 000

Magnetic comparison of cast cobalt magnet steel with rolled steel of the same composition.

It will be noticed that in this comparison the advantage rests with the cast steel, although the difference is but small. The available energy of the rolled metal is less than that of the cast to the extent of about 3 per cent, and the reason for this inferiority is not far to seek. If the two demagnetization curves in Fig. 30 are compared with those for spoiled and unspoiled magnet steel in Fig. 16, it will be seen at once that the difference between the two curves for cobalt steel is of the same character as that which results from partial spoiling, or decomposition of the solute molecules. The spoiling effect is always much more noticeable in cobalt magnet steels than it is in tungsten steels, and in the present example a small degree of spoiling no doubt took place during the heating preparatory to cogging and rolling down the ingot.

Here we light upon an incidental, but most important, advantage possessed by magnet steel in the cast state. It has escaped the liability to dangerous heat treatment which is encountered by rolled steel; a casting only passes once, and that fairly quickly, through the danger zone of temperature.

Having shown that for practical purposes cast magnet steel is just as good as the rolled bar, the next step was to attempt the casting of some typical permanent magnet. The question what is a typical form of magnet was not easily answered. The simplest course would have been to choose some form of magnet already widely used and make an exact copy of it in wood to serve as a pattern for the steel foundry. But to do this would have been to repeat the blunder made by primitive man at the time when he gave up chipping axes out of nodules of flint and took to casting them in bronze. He made the bronze axe exactly the same shape as the stone axe and by so doing preserved the ancient difficulty of fastening the axe to the handle. His sluggish mind took centuries to realize that in casting the bronze a hole might easily be made for the handle.

To copy a rolled steel magnet would have been to turn a blind eye to half the advantage to be gained by casting a magnet. In making a magnet from rolled bar the designer is naturally restricted to such forms as may be readily fashioned by merely bending the bar, a restriction which often involves some sacrifice of magnetic efficiency. There need be no hampering limitation of that kind about a cast magnet, which might evidently be made of any shape the designer chooses, provided the pattern lends itself reasonably well, by its rounded outlines, to the viscous flow of molten magnet steel—a fluid which runs more like thick treacle than limpid water.

With this wide freedom as regards shape, the same considerations that led the designer of dynamos and motors to discard the primitive electromagnet with its yoke and limbs, in favour of the field magnet system of the present day with its internal poles enclosed by a ring casing, suggested that the cast magnet might well take a similar form. One point of advantage possessed by the ring with internal poles is the decreased magnetic leakage, a matter of far greater consequence for a permanent magnet than for the electromagnet. Accordingly several alternative patterns of the ring type were prepared and castings were made from them, both in tungsten steel and in cobalt steel.

Excellent castings were obtained from all the patterns, the specific gravity, determined by weighing in water, giving no measurable indication of porosity. There being nothing to choose between the different castings it was only necessary to select, as a good example of a cast magnet, the pattern which appeared to lend itself best to magnetic and structural requirements. This model is shown in Fig. 31, the upper figure being the casting as received from the foundry, and the lower figure the finished magnet. A cylindrical iron core is shown, fixed concentrically with the polar surfaces to form air-gaps to receive a moving coil of standard

size. The main object being to ascertain the possibility of casting a magnet of ordinary capacity as regards magnetic energy, actual dimensions were of secondary importance. Nevertheless the size of the pattern had been roughly proportioned to an ordinary requirement, on the basis of a casting in tungsten magnet steel. It was intended that the magnet, when fully magnetized, should maintain a magnetic field of about 2 500 in the air-gaps, and a rough computation, based on the demagnetization curve for cast tungsten steel (Fig. 29) showed that to fulfil this requirement the length of the magnet, measured along the magnetic axis, should be about 26 cm, and the total sectional area of the two half-rings in parallel should be about 6·8 cm². The foundry pattern was therefore designed with a view to obtain castings of those dimensions, but beyond this rough adaptation of the size of the magnet to what it was intended to do no attempt was made at any refinement in design.

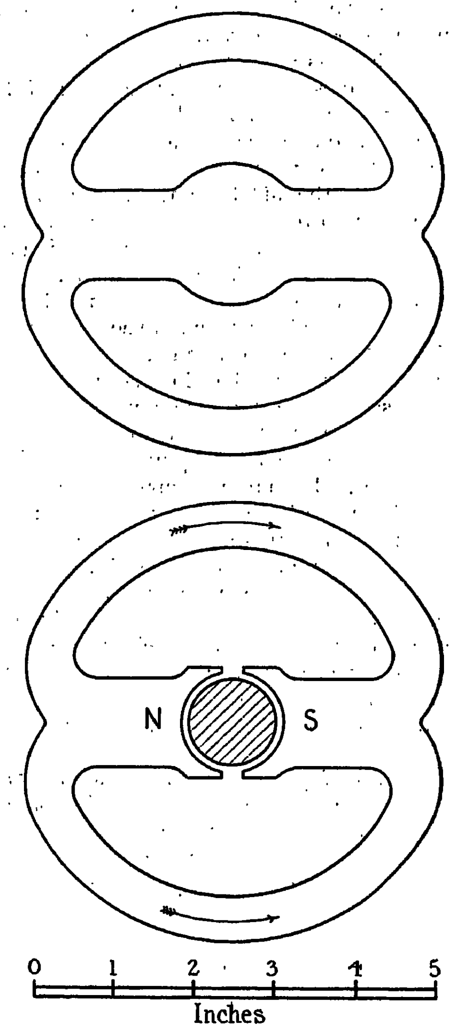

FIG. 31.—A permanent magnet cast in the form of a ring with internally projecting poles. (Cast by Hadfields for the British Scientific Instrument Research Association.)

It was unnecessary to make similar ring patterns of the very different proportions which would be required in magnets made of cobalt steel. There would be no difficulty in doing this in the event of the method of making magnets by casting them proving successful.

The selected tungsten steel magnet was hardened in the ordinary way, by quenching it in cool water from a temperature of 850° C.; no difficulty was encountered and it is clear that the established methods of hardening rolled steel magnets are equally applicable to cast magnets. It was anticipated that with cast steel in in the form of a closed ring, distortion might be a good deal less than in the case of bent magnets of rolled steel. This proved to be the case, the amount of distortion on hardening all the specimen cast magnets, both tungsten steel and cobalt steel, being remarkably small. Too much stress must not be laid on these few examples, however, because the element of chance has a good deal to do with distortion, and it often happens that a bent magnet shows little or no distortion after being hardened.

TABLE 16.

Quantity Compared	Rolled steel magnet	Cast steel magnet
Weight of magnet steel, lb.	4·00	4·47
Weight of magnet with pole pieces, lb...	5·62	4·47
Magnetic field in air-gaps ..	2 330	2 450
Potential difference across the poles	1 080	1 135
Useful magnetic energy, in ergs	1 000 000	997 000

Magnetic comparison of the cast tungsten steel magnet shown in Fig. 31, with a compound bent magnet of rolled tungsten magnet steel.

Having been hardened, the selected magnet was fully magnetized in the direction of the arrows seen in Fig. 31, by means of a current of 1 500 amperes in two temporary coils of 11 turns each, one wound on each half of the ring, the two coils being connected in series in opposite directions. The strength of the magnetizing field applied in this way was 800 per cm of steel, which is more than enough for the complete magnetization of tungsten magnet steel.

The performance of this magnet was in good agreement with the rough predetermination, the measured value of the field in the air-gaps, with the magnet in the fully magnetized state, being 2 450. With a field of this magnitude the potential difference between the polar surfaces is 1 135. The effective air-gap area being about 9 cm², the useful flux would be 2 450 × 9 or 22 000 lines, and the product of useful flux into potential difference is therefore 24 970 000. Dividing the product by 8π, the useful energy maintained by the magnet is found to be almost exactly one million ergs.

This magnet, the first attempt at a cast magnet fit for industrial use, may be compared with a standard pattern compound magnet of rolled tungsten steel. The com-

pound magnet consists of two bent magnets fitted to pole-pieces. These are bored to the same diameter as the polar surfaces of the cast magnet, and the magnetic circuit is completed by a concentric iron core. The effective area of the air-gap path for useful flux is 10 cm^2 in the case of the rolled steel magnet, which compares with 9 cm^2 for the cast magnet; otherwise the air-gaps were identical. Comparative figures for the two magnets are given in Table 16.

As it stands, the experimental cast magnet is in no respect inferior to the rolled steel magnet, and a cast magnet of the same ring pattern, properly designed for the magnetic requirement fulfilled by the magnet of rolled steel, would doubtless show to advantage compared with the bent magnet and its iron pole-pieces.

A useful energy of about a million ergs is not far short of the maximum for a tungsten steel magnet consisting of a single bent bar of rolled steel, without making use of a rolled section of exceptional area. It

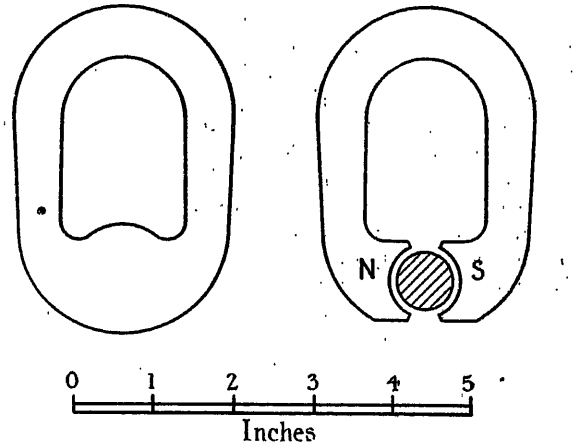

FIG. 32.—A permanent magnet cast in tungsten magnet steel. Designed for uniform flux density and maximum economy, in a form to replace an ordinary bent magnet of rolled steel. (Cast by Hadfields for the British Scientific Instrument Research Association.)

was thought worth while to obtain trial castings in tungsten steel for a magnet of smaller size, more representative of the magnets which are used in vast numbers for electric supply meters and other measuring apparatus.

In addition to the question of size there was another problem to be solved. The introduction of the method of production by casting might well give rise to a demand for cast magnets to replace existing magnets of rolled steel in apparatus of standard design which it might be impracticable to modify. In such cases it would be necessary to adapt the cast magnet to the available space, and the designer might find himself compelled to follow, more or less closely, the conventional shape of the rolled steel magnet which the cast magnet was intended to replace. It was therefore proposed to select some existing instrument containing a small magnet of rolled steel, and to replace it by a cast magnet of the same capacity. The choice fell on a moving-coil voltmeter of conventional type, in which the magnet was closely surrounded by various structures which could not be shifted without an entire reconstruction of the instrument. The cast magnet shown in Fig. 32 was designed to fit into the restricted space without making any alteration in other parts of the instrument.

In the selected instrument the gross magnetic requirement was a field of about 2 000 in two air-gaps constituting an air path 0·479 cm in total length and 5·36 cm^2 in area, figures which correspond with a useful magnetic energy of about 409 000 ergs—less than half the energy of the experimental cast ring magnet. On the basis of these figures the design proceeded and for the first time in any magnet, other than the ellipsoidal bar magnet of the laboratory, the ideal condition of uniform flux density was aimed at. The magnet limbs were designed for a flux density of the economic value already determined for cast tungsten steel from the demagnetization curve given in Fig. 29. It is obviously impossible to fulfil the economic condition in the steel adjacent to the polar surfaces where the flux density necessarily has the same value as the field in the air-gaps and is, therefore, far below the economic value. Away from the immediate neighbourhood of the polar surfaces, a close approach to uniform economic density could have been attained by a somewhat elaborate shaping of the polar ends of the magnet, but in this instance it was regarded as being of the first importance to secure a sound casting, and for this reason simplicity of outline was preserved at the sacrifice of some economy in the utilization of the steel.

The design of the foundry pattern is shown on the left hand in Fig. 32, and the finished magnet on the right. Three or four trial castings in tungsten magnet steel were made from the pattern, all being good sound castings fit for use. Two of the castings were machined and drilled, hardened by quenching from 850° C. and finished at the polar surfaces by grinding. The measured value of the magnetic field in the air-gaps, with the magnets in the fully magnetized state, was in excellent agreement with the predetermined value, being exactly 2 000 in one magnet and 2 130 in the other. Under the same conditions the field maintained by the bent magnet of rolled steel, which the cast magnet was to replace, is 1918, this figure being the average of six of these magnets taken from stock. These figures show that the equipment of existing apparatus with cast magnets is practicable even under rather difficult conditions as regards available space.

With this experiment in replacement the research was brought to a close. The first attempt to make permanent magnets by casting them in magnet steel has met with immediate success from the technical point of view.

The commercial success of the cast magnet depends on which way the balance of the cost of production turns. In the steelworks, the casting of ingots is replaced by the more troublesome process of casting magnets. The cogging and rolling of the ingots into bars, a process which involves the maintenance and running costs of reheating furnaces in addition to rolling-mill charges, would be replaced by the moulding of foundry patterns. Looking at it broadly and making some allowance for the troubles attendant on the production of sound steel castings, it seems that magnet castings should cost less than rolled bar.

Cast magnets greatly simplify the task of the magnet maker. There are no rolled bars to cut into magnet lengths; no bending to shape; no pole-pieces to make, and in their absence no supporting framework to hold magnet and pole-pieces together. The cast magnet is its own support and in the case of the ring pattern with internal polar projections, the magnet may well form the base to which all parts of the working mechanism of the apparatus are attached, much in the same way as the field magnet of the modern motor or dynamo serves to carry the whole machine. Against these favourable points, there will naturally be some additional cost in machining the cast magnet as compared with similar operations on soft-iron or mild-steel pole-pieces; cast magnet steel, even when in the softened state, being much harder than iron.

Upon the whole it appears that both in the steelworks and in the factory of the magnet maker, the balance of cost is likely to turn in favour of the cast magnet, once the initial difficulties of a novel method have been overcome. The development of the cast magnet to the point of commercial success rests quite as much with the magnet user as with the steel founder, because, although most of the troubles will arise in the foundry and be finally overcome there, they will not be overcome, perhaps not even attacked, without an incentive; and the most potent incentive to any manufacturer who is faced with unfamiliar difficulties is an insistent demand.

(24) Hardening.

In the previous section a brief excursion was made into the present century in order to look at cast magnets. We must now return to the Middle Ages in order to carry out the ancient process of hardening, keeping our twentieth century wits about us however.

What happens when magnet steel is hardened has already been described in Section (15). A permanent magnet must have potency, and potency arises from the presence of carbide molecules in solution in iron. But when magnet steel is at room temperature the whole of the solvent iron it contains is, or should be, of the Alpha variety and under ordinary conditions Alpha iron is only capable of dissolving about one-third of the whole amount of carbon present in magnet steel. What is aimed at in the process of hardening is first to dissolve the whole of the carbon while the solvent iron is in the Beta or Gamma state and then to prevent it from passing out of solution when the iron returns to the Alpha state. In that way the steel is endowed with the potency necessary for a good magnet, and, the solvent iron being in the Alpha condition, the steel is fully magnetic.

When magnet steel is ready for the hardening, it will have been brought into the form of a magnet either by bending a piece of rolled bar or by casting the molten metal to the required shape. In either case the steel is likely to be in the softened state. The bent magnet will have been allowed to cool down slowly after the bending operation and there will have been ample time for the whole of the surplus carbide to pass out of solution. The cast magnet must be machined and drilled before it is hardened, and for that purpose it will have been necessary to soften it, the casting as it comes from the foundry being fully ultraheated and therefore too hard for easy machining. It may be assumed, therefore, that whether bent or cast to shape, the steel will be in the softened state when the time arrives to harden it. Moreover, if the effect of ultraheating has been entirely removed, as it should be, by a second heating to 750° C. followed by slow cooling, there will have been a favourable opportunity for crystal growth, and a considerable development in the size of the crystal grains may well have taken place.

The first stage of the hardening process is easy; the whole of the surplus carbide will readily dissolve, provided the solvent iron is of the Beta, Gamma or Delta variety. The iron is therefore converted into Beta by heating the steel to a temperature above the upper boundary of the region within which the transformation from Alpha to Beta takes place. Solution of the surplus carbide then follows as a matter of course. Reference to Fig. 10 shows that in tungsten magnet steel the conversion of Alpha into Beta iron is practically complete at 790° C. In cobalt magnet steel the corresponding temperature, the *dissolving temperature* as it may be called, is considerably higher. Judging from a heating curve, the dissolving temperature for cobalt magnet steel is about 870° C.

Having reached the dissolving temperature, the gradual passage of the surplus carbide from crystal to solution is only a matter of time, since the quantity of iron in the steel, provided it is wholly Beta or Gamma, is capable of dissolving a good deal more carbide than the whole amount present in any kind of magnet steel. It is natural to enquire how long it will take for the surplus carbide to dissolve after the temperature has been raised to the dissolving point. The question does not admit of a precise answer, the available experimental evidence leaving a good many doubtful matters undetermined. When magnet steel is heated slowly the inverse-rate heating curve indicates that the carbide passes from solution concurrently, or nearly so, with the transition of the solvent iron from Alpha to Beta. But when the steel is heated in the ordinary way for the purpose of hardening, by putting it into a fully-heated furnace, the temperature of the metal rises with great rapidity. In these circumstances the progress of the change from crystal to solution apparently lags by an appreciable time behind the allotropic change in the iron, and at the conclusion of the transformation from Alpha to Beta there is still some carbide remaining undissolved. Hence in practice, if the full potency of the steel is to be attained, it is necessary to wait several minutes after reaching the dissolving temperature in order to give ample time for the whole of the carbide to dissolve before the steel is quenched. Under precise laboratory conditions the author has found that a waiting time of 2 minutes is not always enough to ensure complete solution—judging the state of solution from the resulting coercive force of the steel when hardened. On the other hand, in a very large number of hardenings in which the waiting time was increased to 7 minutes there has not been a single instance of failure to secure complete solution. It seems then that the necessary waiting period is somewhere between 2 minutes and

7 minutes, the data at present available not permitting of a more exact statement.*

In the workshop the undisciplined mind has to be reckoned with and the rigid conditions of the laboratory are seldom, if ever, attained. In practice, therefore, ample margins must be allowed both as regards the dissolving temperature and the waiting time. In the author's practice it has been found that it is enough to allow a margin of 50 degrees in temperature, and including this allowance for the shortcomings of the workshop the temperature to which tungsten magnet steel should be raised for the purpose of dissolving the carbide molecules will be 840° C. For cobalt magnet steel the corresponding temperature will be 920° C. At these temperatures the waiting period need not exceed 5 minutes, although no harm (beyond a slight amount of spoiling) will be done by making 10 minutes the rule.

The first stage in the operation of hardening has now been accomplished, the whole of the carbon present in the steel, in the form of carbides, having dissolved in the iron which has been transformed into Beta or Gamma. Whether the solvent iron is of the Beta or Gamma variety is of no practical consequence and, as a matter of fact, with a quickly-rising temperature the change from Alpha to Beta overlaps the conversion of Beta into Gamma, so that atoms of all three varieties may be present together during the transitional stage. But by the time the temperature of tungsten magnet steel reaches 840° C. or that of cobalt magnet steel 920° C., most of the solvent iron, if not the whole of it, will be of the Gamma variety.

The next thing to be done is to cool the steel down to room temperature, and to do it so quickly that there is no time for the surplus carbide to pass out of solution when the solvent iron is transformed once more into Alpha iron. In performing this operation we are taking advantage of the fact that the passage from solution to crystal is essentially a slow process, even when the steel is red hot and the molecular mobility relatively great. As the temperature falls, the mobility decreases with great rapidity and at room temperature it is so slight as to be barely perceptible. Let the steel pass from a red heat to room temperature in a few seconds of time, and before an appreciable fraction of the surplus carbide can pass out of solution the steel is cold and the molecular mobility gone.

Like any other hot body, the steel will lose heat by radiation; but to cool it quickly heat must also be removed by conduction. That is to say, the steel must be brought into thermal contact with a cold body which is a good conductor of heat and, if the cooling is to be rapid enough for the purpose of hardening, the entire surface of the steel must be in close contact with the cold body. In short the cold body must closely envelop the steel, and the simplest way to secure this condition is to have the cooling body in a fluid state. This discovery was made long ago by accident. The discoverer, the primitive blacksmith already referred to, employed water as the cold body, and on the whole water is the most convenient cooling agent. A few other fluids are available; mercury or oil or air may be used, but they none of them serve the purpose quite so well. Water is not only cheap but it has the advantage of being a good conductor of heat, and another point in its favour is a high specific heat. Its one serious disadvantage is its low boiling point. Mercury is an even better conductor of heat and it has a higher boiling point; but its great density is against it, to say nothing of its cost. Oils with a high boiling point are available, but the heat conductivity of oil is much less than that of water. The low specific heat and the inflammability of oil are further disadvantages. Air is plentiful but at ordinary pressures it is a poor conductor of heat compared with either oil or water. Compressed air would be a better conductor and might make a good cooling agent if the obvious practical difficulties in the way of its use could be overcome.

Primitive man ignored all these considerations. Luck was on his side; water was at hand, the red-hot steel was plunged into it and the great discovery was made. The steel was hard.

To-day, with all the accumulated experience of centuries nothing better than water is known and nothing takes the place of sudden immersion. It is true that modifications have been introduced in the hardening of cutting tools, mainly as the result of the use of ultra-heated tungsten and chromium steels. But there is a sharp distinction between the hardening of a tool and the hardening of a magnet, and what answers the purpose of the toolmaker may be quite useless for the magnet maker. In the case of a tool the only parts that need be hardened are those which form the cutting edges. In a large milling cutter, for example, the teeth alone need to be hard, the central core may be left unhardened. Contrast this with the case of the permanent magnet. For a good magnet it is essential to have uniform potency over the entire sectional area, a condition which demands equal hardness throughout, from the surface to the innermost core of the steel. To leave any portion of the transverse section unhardened, or imperfectly hardened, is equivalent to shunting the effective part of the magnet with soft iron and at the same time diminishing the volume of fully potent steel; it constitutes a double weakness. In hardening a magnet, therefore, our object must be to cool the entire volume of steel so quickly that no more than a negligible fraction of the dissolved carbon has time to pass from solution to crystal before the steel becomes cold.

Rapid cooling does not begin at the instant when the steel is taken out of the furnace preparatory to quenching it, and having dissolved the whole of the carbide it is essential that as little of it as possible should be given the opportunity to pass from solution to crystal in the interval between the withdrawal of the steel from the furnace and the moment when rapid cooling begins in the quenching bath. So much of this interval of time as is occupied in moving the steel from the furnace into the bath is under control and with suitable arrangements can be reduced to a negligible duration. But the immediate effect of the sudden immersion in water, for example, is to surround the

* Probably the time necessary for complete solution varies a good deal according to the condition of the steel. It may be conjectured that it depends partly on the extent to which crystal growth has taken place; for the growing of crystal grains is a comparatively slow process and their unbuilding preparatory to solution may be equally slow.

red-hot steel with a heat-insulating envelope of steam, and there is often a sensible delay before the cold water comes into effective contact with the hot metal and sets up rapid cooling. The time spent in this way is largely a matter of chance and is liable to irregular variations. Now during this awkward interval the temperature of the steel is slowly falling, and it may happen that before the conditions for rapid cooling are established, the critical temperature is reached at which the carbide begins to pass out of solution. This contingency must be guarded against by arranging that the temperature of the steel at the moment of immersion shall be well above the critical point; far enough above it to ensure that under the most unfavourable circumstances, as regards delay, rapid cooling shall be in active progress before the temperature has fallen to the critical point at which surplus carbon begins to pass out of solution. The critical temperature for tungsten magnet steel is that given in Section (12), namely 708° C. The corresponding temperature for cobalt magnet steel is 802° C.

The margin of temperature, above the critical points, to be made for the awkward interval between the withdrawal of the steel from the furnace and the beginning of rapid cooling is easily determined by quenching a number of pieces of the steel at different temperatures, appropriately graded, and then measuring their coercive force. An example of this method is given in Fig. 33, which records the results obtained by quenching a number of large bars of tungsten magnet steel from different temperatures, the series being 900°, 850°, 800°, 750°, 720°, 710° and 680° C.* At least two bars were quenched at each temperature, the heat treatment being as follows. Each bar was first heated to 900° C. and kept at that temperature for 10 minutes in order to ensure complete solution of the carbon. The temperature was then lowered to the desired point for quenching and, after keeping the steel at that temperature for 5 minutes, the bar was quenched by allowing it to drop out of the furnace into a tank of cool water fixed immediately below. It will be noticed that at all temperatures down to and including 750° C. the full coercive force of the steel was attained in every case, proving that the whole of the carbon present in the steel in the form of carbides was retained in solution. But at 720° C. there was no such certainty of result. At that temperature the accidental circumstances which give rise to delay in the setting up of rapid cooling after immersion, evidently have a very marked influence on the potency of the quenched steel and it appears to be entirely a matter of chance whether much or little hardening takes place. Since hardness depends on the amount of carbon in solution—and that is governed by the rapidity with which the temperature of the steel is lowered to a region in which molecular mobility is negligible—it is a plausible inference that, at a quenching temperature but little above the critical point, hardness will depend on the rapidity with which the heat-insulating envelope of steam happens to be broken up. But what actually takes place during the brief and turbulent period of quenching could only be ascertained with certainty by the aid of the kinematograph.*

* The tests illustrated in Fig. 33 were undertaken to ascertain the influence of the quenching temperature on cracking, and the temperatures were chosen with that object in view. For a precise determination of the point considered in the text, the series should have included one or two additional temperatures between 700° and 750° C.

From the experiments illustrated in Fig. 33 it is apparent that somewhere between 750° and 720° C. a temperature could be found which just sufficed to guard against the haphazard accidents of quenching. To be on the safe side, however, we may regard 750° C. as the lowest temperature at which tungsten magnet steel should be withdrawn from the furnace for the purpose of quenching in water, the critical temperature of the steel being 708° C. In other words 40 degrees or thereabouts, is a sufficient allowance to make for the slow fall in temperature during the time which elapses between the withdrawal of a piece of steel from the furnace and the actual beginning of the process of rapid

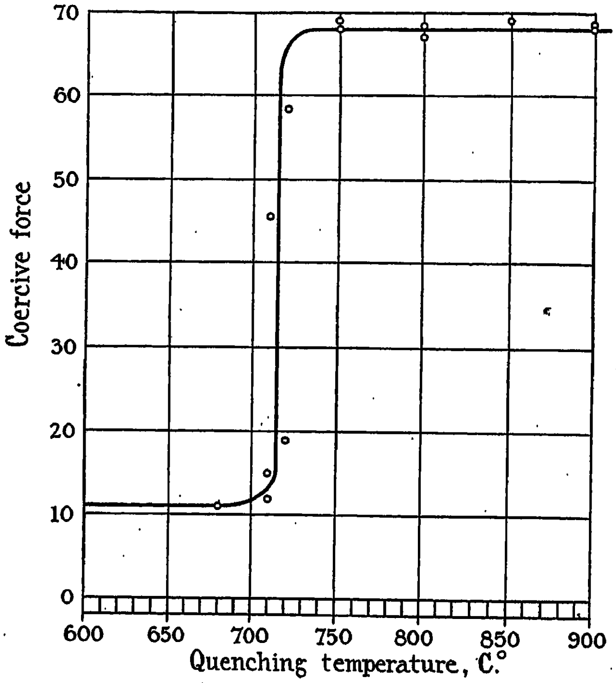

FIG. 33.—Graph showing the coercive force of tungsten magnet steel quenched in water from different temperatures.

cooling by quenching. Since the delay arises from conditions outside the cooling body, the same allowance of 40 degrees will evidently suffice for any kind of steel.

Adding the allowance of about 40 degrees to the critical temperatures, the lowest working temperature, preparatory to quenching in water will be 840° C. for cobalt magnet steel, and 750° C. for tungsten magnet steel. Comparing these figures with the temperatures to which these steels must be raised in order to ensure the solution of the carbon, namely 920° and 850° C, we find

* A point of interest may be referred to in passing. It will have been noticed in Fig. 33 that when the steel was quenched from 680° C. the resulting coercive force was only 11 units. That is to say, although suddenly cooled from a red heat by quenching in cold water, the steel was in the completely softened condition. To those, and they are many, who are rooted in the belief that quenching red-hot steel inevitably hardens it, such a result as this presents a paradox. The explanation is, of course, that in cooling the steel to 680° C. a temperature well below the critical point—the carbon passes rapidly out of solution and including the 5 minutes' waiting time at that temperature, there was more than enough time for the whole of the surplus carbon to pass from solution to crystal. Once that has taken place, quenching can do nothing; it is equivalent to locking the stable door after the steed is stolen.

that the quenching in water could be carried out with full effect at temperatures from 80 to 100 degrees below those required for solution. This difference, arrived at from the conditions occurring in practice, is (as it should be) in reasonably good agreement with the difference between the temperature at which Alpha iron is completely transformed into Beta and that at which the reverse change occurs in the particular steels in question.

The violent method of cooling red-hot steel by quenching it in cold water, subjects the metal, temporarily at least, to severe stresses which are sometimes beyond its strength. On this ground alone it seems desirable to carry out the process at the lowest initial temperature that will ensure complete hardening. To do this it would be necessary after heating the steel to the dissolving temperature, either to lower the heat to the minimum safe temperature for quenching, or to divide the furnace into two compartments or regions of heat, of which one would be maintained at the dissolving temperature and the other at the quenching heat; the pieces of steel being shifted one at a time from one region to the other. But the hardening furnaces in common use at the present time do not lend themselves to any such procedure and hence, in practice, the steel is withdrawn from the furnace at the dissolving temperature and immediately quenched. Whether the liability to cracking is seriously increased, by quenching at a temperature from 80 to 100 degrees higher than is necessary, is a matter which needs investigation.

Among the various matters of secondary importance, connected with the practice of hardening steel by quenching, is the temperature of the cooling bath. This has not been taken into account in the general view of the subject presented in this paper, but some reference to it seems called for in the present section.

Since what is aimed at when red-hot steel is quenched in water is great rapidity of cooling, it is only natural to suppose that the colder the water the better. Primitive man thought so, and in making the sword of the legendary hero it seems to have been considered good practice to harden it by plunging the steel, white hot, into the ice-cold water of a mountain stream. But in these prosaic days the toolmaker knows better. He has discovered that a better result is obtained if the water is slightly warm. Whatever the reason, there is little room to doubt the fact.

What seems to be true of the tool is certainly true of the magnet, the author having observed a small but quite consistent increase in the coercive force of hardened magnets of small size, as the temperature of the cooling water was raised from the freezing point upwards. The effect was traced up to a water temperature of 50° C., at which point an opposing effect obtruded itself and suddenly put an end to rapid cooling. On this account it was found impossible to harden the little magnets when the temperature of the water was raised above 50° C., so long as the quenching was done in the ordinary way by immersion. But with the aid of elaborate means to prevent the formation of an envelope of steam, the increase of coercive force was traced up to a water temperature of 100° C., the increment as the water was raised from 20° C. to 100° C. being no less than 8 units in the case of small bar magnets 0·7 cm in diameter. The warm water effect has not been investigated in larger magnets, but there is good reason for believing that it falls off rapidly as the sectional area of the steel is increased; and in view of the many uncertain factors giving rise to small variations in the coercive force of hardened steel, a possible increase of 1 or 2 units arising from the use of warm water might easily pass unnoticed in workshop practice.

So far as the author is aware, no explanation of the warm water effect has been suggested. It seems not unlikely that it arises from the extremely rapid abstraction of heat from the steel which must take place at the instant when the layer of water in contact with the surface of the steel is suddenly converted into steam, with an accompanying absorption of energy. Assuming it to originate in this way the effect would be proportional to the ratio of the surface of the steel to its volume and would naturally be much greater in magnets of small sectional area than in large ones.

But however we may explain this odd effect, so contrary to our preconceived ideas, there is evidently good reason to follow the practice of the toolmaker by avoiding the use of very cold water. On the other hand, to have the cooling water at a temperature approaching 50° C. would be to court failure, if the quenching is done in the ordinary way. A convenient compromise is to maintain the temperature of the cooling water somewhere between 20° C. and 30° C. The benefit to be derived in this way is small, but since it costs nothing it is worth having.

In the workshop traditional ideas still linger round the practice of hardening, workmen of the older generation being acquainted with many an infallible nostrum. Notwithstanding the legendary use of the pure water of the mountain stream, a favourite notion has been to put something into the quenching water, the workman reasoning perhaps from a familiar analogy. Salt, stale beer, oatmeal, all manner of strange things have been supposed to improve the hardening power of water in one way or another Of all these salt alone has any claim to attention. In so far as the presence of salt, dissolved in the cooling water, raises the boiling point, it probably has some influence on the hardening, but we may search in vain for any experimental evidence of the supposed benefit. For the hardening of cylindrical bar magnets the author has, for many years past, employed a nearly saturated solution of calcium chloride in water, not with any mediæval motive, but in order to put a stop to the frequent splitting of cylindrical bars of steel from end to end when they are quenched in water. There seems little or no reason to believe that a solution of calcium chloride would be of general utility in hardening.

Setting aside the spoiling of magnet steel during manufacture, there is nothing in the making of permanent magnets more in need of improvement than the process of hardening, and surely no other technical process has ever shown so obstinate a resistance to modern ideas. Chemistry, pyrometers, Doctors of Science, metallurgy, electric furnaces, the Higher Education of works managers—all these inestimable blessings have failed to impress themselves on the practice of

hardening magnets. Haphazard, risky, yet clumsily effective, the sudden quenching of red-hot steel in cold water remains a stubborn survival of prehistoric times.

(25) Ageing the Hardened Steel.

It has long been common knowledge that a permanent magnet generally becomes weaker with age, and accordingly when a magnet is to be applied to some purpose where constancy is essential it is usual to submit it to some treatment intended to secure immunity from weakening influences. Any process by which the magnet maker hopes to secure constancy of magnetization is called—somewhat inconsequentially—" ageing " the magnet.

Whether constancy of magnetic power is of much or little consequence depends on the function the magnet is intended to fulfil. In many applications of permanent magnetism the working of the apparatus is little, if at all, affected by variations in the magnetization of the magnet. The magnetic compass, the polarized relay and the moving-coil ohmmeter are examples within this category. In these and some other applications, the acting principle of the instrument requires the presence of permanent magnetism but does not depend on its rigid constancy; the compass, for example, still points to the north even when the magnetic needle has lost a large proportion of its magnetism. But there are other applications of permanent magnetism which depend absolutely on constancy. In moving-coil voltmeters and ammeters, for example, it is essential that the magnetic field maintained by the magnet should be constant; and above all there must be constancy in the brake magnet of an electric supply meter.

It is widely recognized that permanent magnets are apt to suffer from three diseases of a weakening kind, namely, heat, vibration, and the malign influence of stray magnetic fields. To guard against these harmful influences it is common practice, after fully magnetizing a magnet, to weaken it to a moderate extent by an adverse magnetic field, by heat, by vibration, or by any two or all three of these agencies; the idea being that a permanent magnet so treated has, as it were, been innoculated and will suffer no further injury from those three diseases during its useful life. The idea does not rest on good experimental evidence and it would be easy to pick holes in the logic of it, yet mingled with some confusion of thought there is a substratum of sound common sense at the bottom of it.

Much of the confusion will disappear if we begin by drawing a clear distinction between the different causes of loss in magnetic power, according to whether they come from outside the magnet or arise in the steel itself. Stray magnetic fields, heat and vibration all have their origin outside the magnet. On the other hand the gradual loss of potency in hardened steel, disclosed by the experiments described in Section (16), is internal in origin. It is a secular change in the structure of the steel—the molecular pattern which gives the steel its potency, slowly giving way as time goes on. If, as we believe, this slow modification of structure is caused by the passage of carbide molecules out of solution, the change appears to be inevitable in any hardened steel which consists of an over-saturated solution of carbon in Alpha iron. But although it is the steel itself which changes and the cause has nothing to do with magnetism, nevertheless one consequence of the structural change is to rob the steel of some of its magnetic potency by removing the carbide molecules which serve, so to speak, as props to support the magnetic mechanism. Hence if the hardened steel happens to have been made into a permanent magnet the change in the molecular condition, which inevitably occurs with lapse of time, will result in a diminished magnetization. In the present Section attention will be confined to the slow secular change in the hardened steel and the means by which it may be partially forestalled. The weakening effects of stray magnetic fields and different kinds of vibration will be reserved for consideration in subsequent Sections.

It does not appear that anything can be done to prevent the gradual loss of potency in hardened steel as the carbide molecules pass one after the other out of solution and thereby cease to act as supports, but it is an easy matter to forestall the loss. This is done, knowingly or not, by temporarily increasing the molecular mobility by means of heat, and in that way causing any desired fraction of the surplus carbide to pass quickly out of solution before the steel is put to use as a permanent magnet. When this has been done the hardened steel begins life as a magnet with a potency already reduced to a value which in the ordinary course of nature would be reached only after years of slow decay. A certain number of years of natural decay having been forestalled by an immediate reduction in potency, the magnet may be said to have been artificially *aged* by so many years. It is obviously appropriate to describe the process which reduces the potency as " ageing " the steel. This is in fact the only legitimate use of the term and when the hardened steel has been aged in this way the magnet is virtually so many years old, so far as the molecular pattern of the steel is concerned. Ageing in this strict sense has nothing to do with magnetization, and the ageing process may just as well be carried out before the hardened steel is magnetized as afterwards, since it is the steel which requires the treatment and not the magnetization.

There is no difficulty in grasping the principle underlying the practice of ageing magnet steel. The process only differs in degree from the tempering of cutting tools, made of carbon steel, by moderate and temporary heating. In both the aim is to allow just enough carbon to pass out of solution to gain the desired end. The object of the toolmaker is to avoid the extreme brittleness of fully hardened steel and yet to leave enough carbon in solution to give the tool adequate hardness. The object of the magnet maker should be to forestall some years of natural decay in the potency, while leaving enough carbon in solution to give the steel the potency needed for a powerful magnet. It is evident that the two conditions are incompatible, and hence only a compromise is possible.

In the absence of accurate knowledge of the law of decay at different temperatures it is not possible to frame a strict rule for the ageing of magnet steel, but the few facts already available afford some sort of

guidance. Taking tungsten magnet steel as an example, we know from Fig. 21 that within four years from the hardening the coercive force will have fallen from 71·0 to 63·5. By means of the carbon-coercive-force curve given in Fig. 9 these figures may be converted into the percentage quantities of carbon in solution, and it appears that about one-tenth of a gramme of carbon per 100 grammes of steel passes out of solution in the course of the four years after the hardening. Hence to age the hardened steel by four years it will be necessary to heat it to an ageing temperature and then, having allowed one-tenth of a gramme of carbon to pass out of solution, the steel must be cooled again. To determine a convenient ageing temperature, there are only one or two isolated facts to go upon. Referring once more to the experiment recorded in Fig. 12, it will be recalled we pass at once from 345° C. to 100° C., at which temperature the early portion of a decay curve happens to have been obtained in the course of experimental work on another branch of the subject. This curve of decay at 100° C. is reproduced in Fig. 34 and it will be seen that in the course of 7 hours the coercive force fell from 64·8 to 61·4, figures which indicate the passage of about 0·04 gramme of carbon solution to crystal. To occupy 7 hours in the transference of less than half the intended quantity of carbon seems a needlessly slow rate of ageing and it would appear that a temperature somewhat above 100° C. would serve the purpose better. But boiling water is so convenient as a heating agent that the possibilities of ageing at 100° C. may well be examined more closely.

The decay curve in Fig. 34 was obtained from a

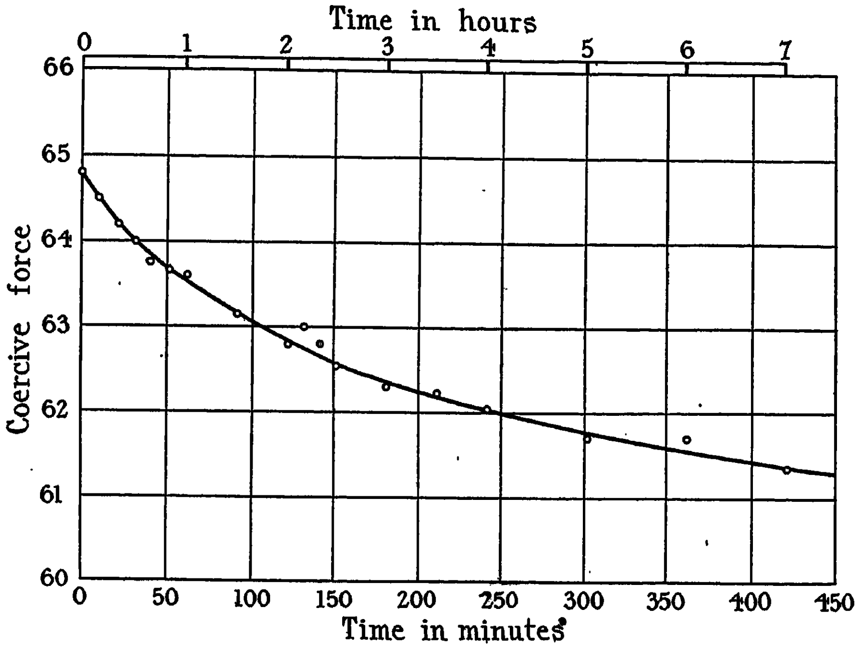

FIG. 34.—Rapid decay in the potency of hardened tungsten magnet steel at a temperature of 100° C.

that when the temperature of the steel was about 700° C. the whole of the surplus carbide, amounting to nearly half a gramme in 100 grammes of magnet steel, passed out of solution in 2 minutes; a rate of one-tenth of a gramme in less than half a minute. Such extreme rapidity is clearly out of the question in an ageing process, and a much lower ageing temperature must be sought. The next indication of a lower rate of transfer from solution to crystal is that given by the curve in Fig. 41.* Here we have the whole of the surplus carbide passing out of solution in 43 minutes while the temperature of the steel falls from 460° C. to 230° C., a mean temperature of 345° C. At that rate one-tenth of a gramme would pass out of solution in about 9 minutes and, although that might not be too rapid under laboratory conditions, so short a time would certainly lead to mishaps in the workshop. No experiments at intermediate temperatures being available, tungsten steel magnet which had already been in the hardened state for 77 days, during which time the early and more rapid natural decay had been in progress. Hence if a true comparison is to be made between ageing at 100° C. and natural decay at room temperature, the decay shown in Fig. 34 should be compared with what goes on at room temperature after the lapse of 77 days from the hardening. Now the curve of natural decay given in Fig. 21 shows that 77 days after the hardening the coercive force had declined to 66·5, and that during the subsequent period of 1 215 days (or 3·33 years) the coercive force fell to 63·8. This is a decrease of 2·7 units in 3·33 years, an average rate of decay of 0·81 unit a year at an average temperature of about 18° C. Comparing this with the rate of decay at 100° C., we notice that in Fig. 34 the coercive force decreases from 64·8 to 62·1, a fall of 2·7 units, in 3·67 hours, an average rate of 0·74 units an *hour* at a temperature of 100° C. The ratio of the figures 0·81 and 0·74 being 1·1, it

* See Appendix, page 803.

appears from this comparison that in hardened tungsten magnet steel the loss of potency which occurs in a year under the ordinary conditions of natural decay, takes place in 1·1 hours when the temperature of the steel is raised to 100° C. Strictly speaking this proportion only applies to the progress of decay when 77 days have already elapsed since the hardening, but by far the greater part of the decay occurring in that time takes place within a few hours after hardening, and hence it seems very probable that the proportion would have been much the same if the comparative periods at 18° C. and 100° C. had begun very much earlier. Making that assumption, a provisional rule for ageing hardened magnet steel at 100° C. may be given. In practice it will be convenient to divide the ageing into two stages. Immediately after the hardening the loss of potency goes on so quickly that the steel may very well be left at room temperature for 24 hours or so to age itself. During that time the coercive force of tungsten steel will decline by about 3 units, and cobalt steel will lose 6 or 7 units. This early and rapid decline having taken place at room temperature, the first stage is over. The second stage is to forestall the subsequent slow progress of natural decay by maintaining the hardened steel at 100° C. The heating is most easily done with the necessary precision by putting the steel into boiling water, and the duration of this heat treatment must be determined by the provisional rule that each period of 1·1 hours at 100° C. adds one year to the "age" of the hardened steel. The experimental data on which this rule is founded leave much to be desired, but once the underlying principle is recognized there should be little difficulty in obtaining more accurate measurements of decay at different temperatures, and the provisional rule can then be amended accordingly.

There is no simple relation between the decay in potency, as measured by the Hopkinsonian coercive force, and the consequent falling off in the useful magnetic energy which a permanent magnet maintains. An example of the effect of decay on the course taken by the demagnetization curve has been given in Fig. 23. The curves in this instance were obtained from cobalt magnet steel, in which the phenomena of decay are particularly prominent and on that account the more easily observed with accuracy. As determined from the demagnetization curve taken one day after the hardening, the economic flux density in the particular specimen of cobalt steel was 6 000, and the magnetic energy maintained by a magnet designed for economy of steel would have been 27 200 ergs per cm^3 at that age of the hardened steel. The demagnetization curve obtained from the same magnet after the lapse of 1 006 days (2·9 years) shows that the amount of energy which the magnet was capable of maintaining, after being again fully magnetized, had fallen to 23 900 ergs per cm^3 of steel, as the result of decay; a decrease of 12 per cent. In the same time the coercive force diminished from 175·0 to 161·5, a decrease of 7·7 per cent. The ratio of the two percentage figures is 1·57 and in this instance, therefore, the loss of useful magnetic energy was 1·57 times the loss of coercive force.

A little consideration will show that some such proportion may be anticipated from first principles. Decay is the removal of carbide molecules from the solution positions in which they give the steel its potency. For small changes, the percentage decrease in coercive force is a rough measure of the proportion of carbon passing out of solution, and since each carbide molecule controls a group of magnetic molecules, giving the group its individual potency, a loss of 7·7 in coercive force implies a corresponding diminution in the number of active groups in the magnetic mechanism. Hence without taking into account the greater magnetic freedom which the active groups acquire when some of their neighbours lose their potency, the magnetomotive force and flux density should each diminish by about 7·7 per cent, and the loss of useful magnetic energy would therefore be about 14·8 per cent. But in virtue of the greater freedom which they have acquired, the active groups will slightly increase their orientation and thereby provide a small additional magnetomotive force. Hence although the active groups will be fewer in number each of them will have a slightly greater magnetomotive force, and the small individual gain must be set off against loss in numbers. What the gain would amount to there is no present means of knowing, apart from what can be ascertained from the demagnetization curves themselves. In the present example the difference between the roughly computed figure for the loss of useful energy, namely, 14·8 per cent, and the observed loss of 12·0 per cent, would be explained if the magnetomotive force of the oriented magnetic molecules in each individual active group increased by about 1·4 per cent, an amount which would be well accounted for by the slightly greater freedom of independent magnetic action which active groups acquire as the result of other groups becoming inactive.

The figures for the comparison made in the last paragraph were obtained from cobalt steel. Decay occurs on a much smaller scale in tungsten steel, and a similar comparison between loss of coercive force and loss of useful magnetic energy is not so easily made with accuracy. But the magnetic characteristics of the two steels differ in degree rather than in kind, and in all probability the magnetic effects of decay seen in Fig. 23 are typical of both steels so far as the relative magnitudes of comparatively small changes are concerned. To sum up the facts so far as they are known at present, the effects of the decay of potency on the magnetic properties of a permanent magnet (made of any kind of steel) are a loss of coercive force and a consequential loss in the useful magnetic energy which the magnet can maintain when it has been fully magnetized; the percentage loss of energy being from 1·5 to 1·6 times the percentage loss of coercive force.

It will not have passed unnoticed that the comparison drawn from the demagnetization curves given in Fig. 23 is made between a newly magnetized magnet one day after the hardening, and the same magnet when, after the lapse of 1 006 days, it was completely re-magnetized —a refreshment that does not come to a magnet in ordinary use. In other words, the comparison was one between the useful magnetic energy which an economic magnet maintained when one day old and immediately after magnetization, and the maximum energy which

the same magnet was capable of maintaining when re-magnetized after suffering natural decay for a period of 1 006 days. On that basis the observed loss of useful energy was 12 per cent. It is not possible to give even an approximate figure for what the loss would have been under the ordinary conditions of use with the magnetization slowly giving way as the potency of the steel decayed. Obviously the loss would not have been less than 12 per cent; almost certainly it would have been considerably in excess of that figure, even if the magnet had been carefully shielded from every weakening agency other than decay in the steel.

(26) Magnetic Stability: Resistance to Stray Fields.

We may now suppose the steel to have been hardened and aged. The next step is to magnetize it, and having done that the stability of the magnetization must be considered. It will be convenient to take as an example a particular magnet from which complete experimental data have been obtained. The magnet was made of tungsten steel and, being of ellipsoidal form and designed for economy of steel, it represents the ideal case of a simple magnetic circuit of magnetized steel in series with an air-gap, the magnetic field in the gap being maintained with maximum economy. Magnetization was effected by placing the magnet in the uniform magnetic field of an exciting coil, and in what follows we shall distinguish between the magnetic field created by the oriented magnetic molecules of Alpha iron in the steel—the *self-created field*—and the additional field supplied by the exciting coil—the *coil field*. The sum of the two fields constitutes the flux density in the magnet as it would be observed by search coil and ballistic galvanometer. The two fields act together as the orienting magnetic field—the field which compels the magnetic molecules to take up angular positions in which their magnetomotive forces are directed more or less along the magnet. The flux in the magnet may be either augmented or diminished by the exciting coil according to the direction of the current, and, for convenience in reckoning, the orienting field may be regarded as the algebraic sum of the self-created field and the coil field.

The magnetic mechanism of the permanent magnet, as seen through the mental microscope constructed by Ampère, Weber and Ewing, has been described in the previous paper. The magnetic machine is composed of groups of magnetic molecules, each group being capable of existing in stable equilibrium either as a closed magnetic circuit which has no magnetic action beyond its own confines, or as an open magnetic circuit in which the constituent molecules are all more or less oriented in one direction. Orientation gives the group a resultant magnetomotive force in the direction of the magnetic field by which the orientation was effected. In the unmagnetized steel every group is in its primitive condition as a closed magnetic circuit, and magnetization consists in compelling the primitive groups to re-arrange themselves as oriented groups. This is effected by the orienting field, which applies a deflecting moment to every magnetic molecule.

To understand the process of magnetization in iron and steel it is necessary to bear constantly in mind the fact that the self-created field is, by itself, very nearly enough to maintain the magnetic mechanism in the oriented state. Very nearly, but never quite enough, and a small addition to the orienting power of the self-created field is needed for equilibrium. In the electromagnet (and our permanent magnet during magnetization is in effect an electromagnet) the additional orienting force is provided by the coil field. In iron and steel the necessary additional deflecting force—the balance, so to speak—is always small compared with the force of the self-created field, and hence the oriented mass of molecules never possesses more than a small margin of stability and sometimes no margin at all. It follows that a trifling change in the balancing force is often enough to cause a very large change in the magnetization.

To obtain the greatest possible magnetic power in a permanent magnet, every primitive group in the steel must be converted, temporarily at all events, into an oriented group. What strength of orienting field is needed to do this is not known with any certainty, but so far as it is possible to judge from magnetization curves of iron and steel, a magnetic field of between 15 000 and 16 000 is enough for the purpose. No ordinary exciting coil can possibly create a field of such magnitude, but what the coil cannot do the inherent magnetomotive force of myriads of magnetic molecules of Alpha iron will easily accomplish if only they can be induced to orient themselves. They need a little assistance to begin with, something to deflect them a little in the required direction; and that assistance is given them by the field of the exciting coil.

We proceed to magnetize the magnet, initiating the all-but automatic process by means of a coil field of small magnitude. Aiming at an orienting field of about 16 000 so as to ensure the conversion of every primitive group into the oriented state, we find by experiment that the tungsten steel magnet requires an orienting field of about 16 500 to maintain an orientation sufficient to generate a self-created field of 16 000. Accordingly the coil field is raised to 500, the oriented molecules generate a field of 16 000, and magnetization is assumed to be complete; every group of magnetic molecules has been compelled to orient itself.*

Having fully magnetized the magnet or, rather having with a little assistance induced the magnetic molecules to orient themselves, thus building up a wonderful arrangement of oriented groups, the exciting current is cut off and the coil field falls to zero. With the loss of the small balancing force needed for their equilibrium, the oriented groups begin to return one after the other to the primitive state. The disappearance of their magnetomotive force causes the self-created field to fall off to a corresponding extent, thus upsetting the equilibrium of other oriented groups. In short the elaborate oriented edifice comes tumbling down like a house of cards, and if it were not for the mutual induction of the constituent molecules of each

* For the complete magnetization of cobalt magnet steel the coil field should be at least 1 000 to arrive at an orienting field of 15 000 or more. It is worthy of notice in passing that even in the rather extreme case of the magnetization of hardened magnet steel as an electromagnet, the magnetic molecules in tungsten steel generate 97 per cent of the whole flux, and in cobalt steel 94 per cent. The exciting coil only generates the balance of 3 per cent and 6 per cent respectively.

oriented group (a magnetic bond which gives the group a limited power of self-preservation) the downfall would be complete.

Any self-preserving power possessed by an oriented group arises from the flux generated by the constituent magnetic molecules in local paths adjacent to the group, and the strength of this magnetic bond depends on how much space is freely available for the flux. If an oriented group could be isolated and afforded unlimited free space, its power of preserving itself as an oriented system would be a maximum. On the other hand, when an oriented group is closely surrounded by other oriented groups, the self-preserving power is greatly restricted by mutual magnetic interference, the different groups all competing for the same space. Under such conditions any individual group can only monopolize groups to revert to the primitive state. At what stage in the downfall the orienting forces arising from the local magnetic bonds will add just what is required to the orienting force of the self-created field in order to balance the de-orienting forces, cannot be foretold. Equilibrium will depend partly on the molecular pattern of the steel, and partly on what proportion of the whole length of the magnetic circuit is occupied by the magnetic generating mechanism contained in the hardened steel. But whatever the particular values of these determining factors may be, the growing strength of the magnetic bonds which hold the oriented groups together must sooner or later provide the small balance needed for equilibrium in what remains of the oriented system. At that point the downfall is arrested and the permanent magnet is born.

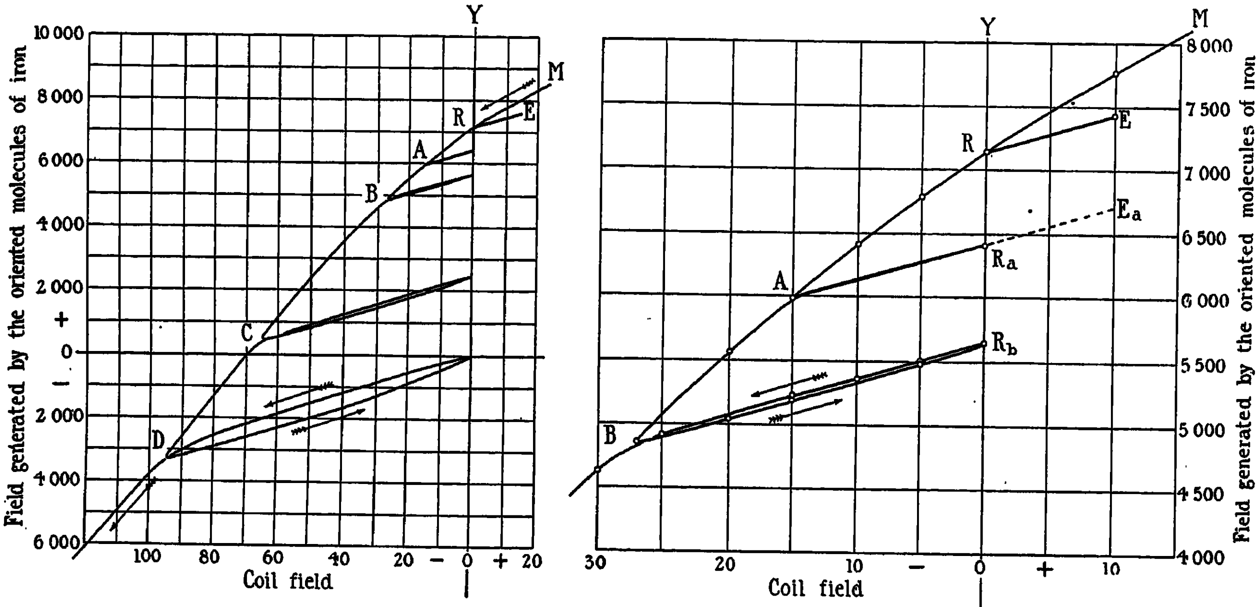

FIG. 35.—Demagnetization curve obtained from the magnetic circuit of a permanent magnet of tungsten steel, showing four recoil loops. The upper portion of the curve, with two recoil loops, is shown in the right-hand figure on a greatly enlarged scale.

a very small portion of the adjacent space and, the local flux paths being confined within narrow limits, the magnetic bond or self-preserving power is much reduced in strength. It follows that when all the groups in the magnet were oriented in the course of magnetization, their self-preserving power was at a minimum. But the coil field has now been reduced to zero and oriented groups are rapidly returning to the primitive state, thereby diminishing the magnetic interference experienced by groups which remain oriented. As the downfall of magnetization proceeds, the remaining oriented groups gain more and more freedom to act as independent magnetic systems, and the magnetic bonds which hold them together grow in strength. In this way self-preservation comes into play as an active deflectional force assisting the self-created field in maintaining the orientation of the magnetic mechanism, and ultimately these two forces acting in the orienting direction will balance the forces which tend to cause oriented

The downfall of the system of oriented magnetic molecules is represented by the demagnetization curve. For the magnet taken as an example, the approach to equilibrium at the point of arrest is indicated in Fig. 35 by the line MR which forms part of the demagnetization curve of the magnetic circuit of magnet and air path. In the diagram the self-created field is indicated by the vertical co-ordinates, and the horizontal co-ordinates give the amount by which the self-created field is augmented or diminished by the coil field. The sum, or difference, of the vertical and horizontal co-ordinates of any point on the curve gives the magnitude of the orienting field. It has already been noticed that this is the quantity which, when measured by search coil and ballistic galvanometer, is called the flux density in the magnet. The diagram represents the magnetic condition of the steel in a magnetic circuit composed of magnet and air-gap in series, and in the absence of any magnetomotive forces, other than those inherent in

the magnetic molecules, the magnetic field inside the steel will be indicated by some point on the vertical axis OY. Immediately after magnetization, equilibrium was established at the arrest point R. The coil field being zero, the self-created field indicated by the point R is the same thing as the orienting field or the flux density in the magnet, a particular value generally described as the remanent flux density of the magnet. In the present instance the remanent flux density was 7 150 at the moment when the downfall of the oriented system was arrested at R.

Although the magnetization of the steel is in equilibrium at the point of arrest, there is no margin of stability, and any further diminution of the orienting field will renew the downfall of the oriented system. Hence, if the field is diminished by an adverse coil-field the demagnetization curve will be continued from R downwards towards the point A. But the converse does not hold good. It is, of course, well known that if the remanent flux density is augmented by the addition of a coil field in the same direction, the demagnetization curve is not retraced along the line RM. It takes a course lower down and in the present example it was found by experiment that upon adding a coil field of gradually increasing magnitude the magnetization followed the line RE. It was further noticed that within narrow limits of observational error the trace from R to E was a straight line, the increments of self-created field being simply proportional to the increment of coil field, provided the latter did not exceed about 15 units. Again, on gradually decreasing the coil field to zero, the magnetization returned to the point R, the trace returning along the same line from E to R.

To understand the nature of the equilibrium in the magnet as a whole when the magnetization is at a point of arrest, we must attend to the conditions of equilibrium in an individual oriented group. The constituent magnetic molecules, in virtue of their magnetic moments as current rings, experience turning moments in contrary senses, and their angular positions of equilibrium are determined by the balance of these clockwise and counter-clockwise forces. Two turning forces act in the orienting sense. There is the moment due to the orienting field and under conditions already referred to there is an additional turning moment, in the same sense, arising from the local flux generated by the group as an independent oriented system. Acting in the opposite sense is a de-orienting moment. To trace the de-orienting moment to its source would land us in many difficulties, but it will suffice for our present purpose to recognize the existence of a negative or backwards turning moment, a de-orienting moment which is constantly tending to deflect the molecules away from their oriented positions towards angular positions at which they suddenly lose stability, and return to their primitive state as a closed magnetic circuit.

The angular positions of the magnetic molecules when the oriented group is in stable equilibrium may be denoted by θ_s, and the average angle at which the molecules become unstable by θ_u. The margin of stability will then be defined by the difference $\theta_s - \theta_u$, the margin angle. Increasing the orienting field increases θ_s, and as θ_s grows the margin grows. On the other hand if the orienting field decreases, θ_s gradually approaches θ_u, the angle of instability, the margin becoming smaller and smaller. Obviously, the magnetic molecules in any oriented group which has a margin of stability may be deflected on either side of their equilibrium angle θ_s without loss of stability, provided the deflection is less than the margin angle $\theta_s-\theta_u$; moreover, when the turning moment which caused the deflection is withdrawn, the molecules will return to their equilibrium angle θ_s.

To impart stability to the magnetization of the magnet, our aim must be to ensure that every oriented group in the magnetic mechanism has an adequate margin of stability; there must be no oriented groups in which $\theta_s-\theta_u$ is zero. Now the magnetic mechanism of the magnet is composed of an assemblage of crystal grains of Alpha iron in which crystal growth has taken place at all sorts of different inclinations. Hence if the group which forms a unit in the magnetic machine is identified with the elementary crystal group, the natural magnetic axes of the oriented groups will point in many directions. It is not difficult to see that, whatever the stage of magnetization may be, this variety of inclinations in the structure of different crystal grains must give oriented groups widely different degrees of stability. During the downfall of magnetization, different groups would vary in stability from a maximum to no margin at all, the groups with no margin being those in which the magnetic molecules, having arrived at the end of their tether, are on the point of reverting to the primitive group-form, as the gradual diminution in the orienting field continues.

With the aid of this picture of oriented groups, the difference between continued downfall from the arrest point R, and a return along the line RE, is readily explained. Downfall consists in oriented groups reverting to the primitive state, their constituent molecules toppling over into that arrangement when they reach the end of their tether as parts of an oriented system. Hence when the orienting field is diminished, after arriving at an arrest point, every group which happens to have reached the point of instability will immediately return to the primitive state, and the demagnetization curve from M to R may be continued towards A without a break by means of an adverse coil field which serves to diminish the orienting field. On the other hand, if the orienting field is augmented by means of a coil field acting in the same direction as the self-created field, then the magnetic molecules in every group will swing round through a small angle in the orienting sense. The effect of this general movement will be to deflect all those molecules which happen to have arrived at the end of their tether into angular positions a little removed from their positions of instability, thus giving them, and the oriented groups to which they belong, a margin angle of stability. In other words, those groups in which $\theta_s-\theta_u$ was all but zero will acquire a definite margin measured by the angular difference $\theta_s-\theta_u$. Incidentally the general movement of deflection, resulting from the increase in the orienting field, will add to the margin angle of all those groups which already had more or less margin. It is clear, however, that on increasing the orienting field by any

given amount, the margin of stability imparted to the magnet as a whole will be neither more nor less than the margin given to those oriented groups which, at the moment of arrest, were on the verge of instability. The weakest link in the chain determines the strength.

In considering the effect of the coil field, the cumulative action of the magnetic molecules themselves must always be taken into account. In the present case the effect of making a small addition to the orienting field, by means of a coil field, is a general increase in the angle of orientation of the molecules. The immediate result is an increase in their effective magnetomotive force and consequently in the self-created field. This is an addition to the orienting field and brings about a further addition to the angle of orientation, the cumulative action going on until the falling off in the moment of the orienting force arising from the local flux created by each oriented group, balances the gain due to the increased orienting field. At that point a new equilibrium is established.

In the tungsten steel magnet which has been chosen as a typical example, the remanent flux density—self-created field, or orienting field—was 7 150 at the arrest point R. The instantaneous effect of the addition of a coil field of 10 units is to raise the orienting field to 7 160. But, by experiment, it was found that as the result of the cumulative deflectional movement of the magnetic molecules in an orienting sense, the self-created field actually rose from 7 150 to 7 430, an increase of 280 units. That is to say the coil field of 10 units initiated changes in the angular positions of the molecules which gave them a greater effective magnetomotive force, and the outcome was an increase of 280 units in the self-created field, each unit of coil field inducing the magnetic molecules to generate 28 units. For small deflectional changes, such as we are now considering in connection with the line RE, there should be simple proportionality between increment of coil field, increment of deflection, increment of magnetomotive force and increment of self-created field. Hence from what we can make out of the behaviour of magnetic molecules we should expect to find the connection between coil field and self-created field in the region between R and E expressed by the straight-line law which experiment has already disclosed.

So far as can be ascertained by magnetometer readings of precision, the proportionality of self-created field to added coil field holds good for values of the latter up to 15 units or more, the first clear indication of any departure from a straight-line law occurring with a coil field of 20 units. In the diagram, therefore, the arithmetical relation of the two fields is represented by a straight line from R to E, and any departure from strict proportionality, either with increasing or decreasing magnitudes, is well within the thickness of the line. This simple state of things can only hold for such changes of the self-created field as can be made by deflecting the magnetic molecules one way or the other within their marginal angles of stability. When those limits are exceeded on either side of the angle of equilibrium, then on the one side oriented groups will revert to the primitive state and on the other side primitive groups will be compelled to orient themselves. In either case the transition from one group-form to the other involves a loss of energy, and the changes in orientation angle, in effective molecular magnetomotive force, and in magnetic fields, are no longer in simple proportion. This state of things is indicated by the line RE beginning to curve upwards, the return line ER showing a corresponding curvature downwards, and the two lines then form a narrow loop enclosing an area. The area of the loop is, of course, a measure of the loss of energy, the hysteresis loss resulting from the unstable movements of the molecules when groups change from one form to the other.

There is a close analogy between the oriented group which has a margin of stability, and the more familiar elastic spring. Just as the spring, in virtue of its elasticity, may be deflected in either direction within the elastic limit, so the constituent magnetic molecules of the group may be deflected either way within limits; and just as the spring returns to zero when the deflecting force is removed, so the magnetic molecules return to their angular positions of equilibrium. When every oriented group in a mass of magnetized iron or steel has been endowed with a margin of stability, the whole magnetic mechanism, the whole magnet, responds to variations in the strength of the orienting field in a spring-like fashion, a condition of deflectional stability in orientation which has been described by Ewing as one of quasi-elasticity.* To retain the idea without suggesting all that is implied by the word elastic we shall refer to magnetized iron and steel which has been brought into the pseudo-elastic condition as being in a state of *recoil* † and lines drawn from an arrest point and back again, like the line between R and E in Fig. 35, will be described as *recoil lines* or *recoil loops* as the case may be.

The downfall of magnetization can be arrested at any point by adjusting the coil field to the appropriate value, either adverse to the self-created field or in the direction to assist it. In the example already considered the downfall was arrested at the point R, Fig. 35, by reducing the coil field to zero, and recoil was traced from R to E and back again to R. Other recoil lines are shown in the diagram originating at the points of arrest A, B, C and D. At each of these points the condition of the magnetic mechanism as regards stability is similar to that already described in connection with the point R. That is to say, there will be numerous oriented groups of magnetic molecules on the verge of instability, and to give them a margin the orienting field must be increased so as to cause the molecules to swing away from their precarious positions and take up angular positions of equilibrium which give them a margin. When the downfall of magnetization is to be arrested at a point on the left-hand side of the axis OY, the arrest is brought about by means of a coil field in the opposite direction to the self-created field, and the increase in the orienting field which is required to give a margin of stability is effected by gradually reducing the strength of the adverse coil field.

The recoil lines from the points A, B, C and D were traced by experiment from the point of arrest to the

* J. A. Ewing: "Magnetic Induction in Iron and Other Metals" (1893), chap. 11.

† Recoil:—v.t. to start back. From French *reculer*. No connection with the coils of a spiral spring, or with the exciting coil of a magnet.

axis OY and then back again to the main demagnetization curve. An adverse coil field of 15 units served to reduce the self-created field from 7 150 at R to 5 980 at A, and from this point of arrest the recoil line was traced by reducing the coil field step by step to zero. The consequent increase in the orienting field gave rise to an increase in the self-created field which finally reached the value 6 410 on the axis OY, an increase of 430 units. Dividing 430 by 15 we find that along the recoil line from A each decrement of one unit in the coil field (or increment of one unit in the orienting field) results in an increase of 28·6 units in the self-created field, the field generated by the magnetic molecules. It was just possible to distinguish a slight curvature in the recoil from A, and when the line was traced beyond the axis OY, as indicated by the dotted line, the direction of recoil became very nearly parallel with the corresponding recoil line RE. We have already noticed that along RE the increment of self-created field is 28 times the increment of coil field, and it is now seen that in the course of recoil from the point A this proportion has the value 28·6 on the left-hand side of the axis. Continuing the line of recoil on the right-hand side towards E_a, a small curvature in the upward direction can just be distinguished. As the point of arrest falls further and further down the curve of demagnetization, curvature of the lines of recoil becomes more prominent; partly because of the greater horizontal distance between the arrest point and the axial line OY and partly by reason of the decreased flux density. Judging by the rapidly growing area of the recoil loops, it would seem that the molecular groups change from one form to the other more readily in weak orienting fields than they do in stronger fields. It may be noticed in passing that the position of the arrest point D was so chosen that, upon recoil, the magnet was left in a completely demagnetized condition.

We now have to consider how far the state of recoil renders a permanent magnet immune to stray magnetic fields, and it will be convenient to begin with the most unfavourable case—that of the bar magnet. We have an example of a bar magnet ready to hand in the ellipsoidal magnet of tungsten steel to which Fig. 35 relates, and we may suppose this magnet to have been brought into a state of recoil from the point A by the application and removal of an adverse coil field of 15 units, the remanent flux density in the magnet being indicated by the point R_a. If the magnet, when in this condition, comes under the influence of a stray field not exceeding 15 units and acting in the adverse or weakening direction, the temporary effect will be to carry the magnetization to some point on the line R_aA. On the disappearance of the stray field the magnetization will return along the line of recoil to the remanent point R_a. If the stray field had been in the assisting or strengthening direction the magnetization would have been carried to some point on the extended line by recoil R_aE_a, and again, on the disappearance of the stray field, the magnetization would return along the recoil line to R_a. Hence a bar magnet which has been brought into a state of recoil by the temporary application of an adverse coil field of given strength is immune to stray fields which do not exceed that strength, immune in the sense that the strength of the magnet is not permanently affected one way or the other by the stray field. But the proviso must be made that immunity is only absolute so far as recoil follows a straight-line law. As recoil lines acquire more and more curvature, giving rise to recoil loops, so the immunity from stray fields becomes less perfect; but even so the extent of the permanent change in the strength of a bar magnet, following the action of a stray field, will always be limited to an amount not exceeding the vertical width of the loop.

So much for the immunity of the bar magnet. The only other case which need be considered here is that of the bent magnet with two straight and parallel limbs. We shall again assume that recoil has been effected by an adverse coil field of 15 units, leaving the magnetization at the point R_a in the diagram. Obviously any stray magnetic field which is uniform throughout the space occupied by the magnet will act equally but in opposite directions in the two limbs of the magnet. Hence in one limb the temporary change in magnetization will follow the recoil line R_aA and in the other limb the line R_aE_a. Although these two lines are nearly straight they are not exactly in line with each other, and hence the temporary change in one limb will not be exactly neutralized by the contrary change in the other limb. Nevertheless, the difference will be very small and where a bar magnet would suffer a considerable temporary change of strength, the change in the bent magnet would be hardly perceptible. On the disappearance of the stray field, the magnetization in each limb of the bent magnet will return to the point R_a, the strength of the magnet not suffering any permanent change provided the stray field has not exceeded the magnitude of the coil field which effected the recoil.

The method of imparting stability to a permanent magnet by recoil from some point on the main demagnetization curve leaves little to be desired, except on the score of symmetry on either side of the remanence line of the magnet; a want of symmetry which arises from the fact that the recoil lines R_aA and RE_a are not exactly in line with each other. It is, however, easy to obtain exact symmetry by first adjusting the coil field to the desired value for recoil and then reversing its direction half a dozen times or more by means of a reversing switch in the circuit of the coil. An example of a symmetrical recoil loop is shown in Fig. 36. The scale of the diagram has been magnified almost to the limit of what the magnetometer readings would bear, in order to exhibit the characteristic features of recoil loops as clearly as possible. The magnetometer readings were taken after 15 reversals of the coil field, by which time the orientation had settled down into a condition in which the cyclic change followed the same course time after time. It will be seen that in the case of a bar magnet the permanent effect of a stray magnetic field of 15 units acting in the positive direction would be to leave the magnetization at the point R_2, whereas if the stray field had been in the negative direction the magnetization would be left at R_1. At these two points the flux density was 6 410 and 6 380 respectively, a difference of 30 units or 0·47 per cent. This is the maximum permanent change in strength which could

be effected by the temporary existence of a stray field of 15 units. A refinement in the method of the symmetrical recoil loop is to reduce the coil-current step by step to zero while the reversing switch is worked to and fro. This has the effect of performing a number of cyclic changes in the coil field with a gradually decreasing amplitude, finally ending at zero and leaving the magnetization at a point midway between R_2 and R_1. In a bar magnet which has been brought into this condition of ideal symmetry, the greatest permanent change in strength which could be caused by a stray field of 15

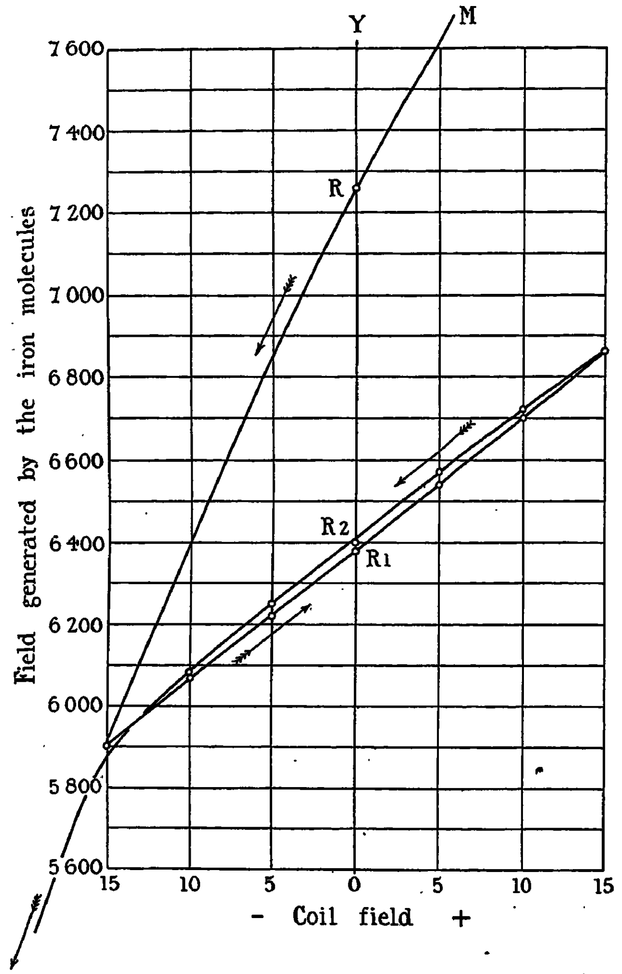

FIG. 36.—A recoil loop symmetrical about the axis of remanence, OY.

units would be less than 0·24 per cent; and a bar magnet is the worst case.

In the foregoing description of the method of giving a margin of stability to a magnet it has been assumed, for simplicity of statement, that the exciting coil used for the magnetization is afterwards available for creating the adverse coil field which serves to shift the orientation into a condition of recoil and stability. In practice, however, it is not generally convenient to use the magnetizing coil for this purpose, and a separate coil must be provided. A coil intended to impart stability may take the form of a pair of large Helmholtz coils giving a uniform magnetic field of any desired value up to about 20 units throughout a space big enough to contain the largest magnet.

What is done by reversals of direct current may be done by alternating current. But it is essential that the coil field should penetrate to the centre of the magnet section, and to fulfil that condition in a bar of steel, perhaps half an inch in thickness, a supply of alternating current at very low frequency would be required. On the whole, the advantage seems to rest with direct current and a reversing switch.

After being fully magnetized, a permanent magnet has its maximum strength when the magnetization has been allowed to settle down at the natural arrest point, R in Fig. 35. This is the point of maximum remanent flux density, and shifting the orientation of the magnetic molecules into a state of recoil, in order to give the magnet a margin of stability, involves a loss of strength. It is seldom that the magnitude of the stray magnetic fields to which a magnet may be subjected can be foreseen, and the designer can only exercise his judgement in determining what sacrifice of strength to make for the sake of securing immunity from the effects of stray fields which a magnet may or may not encounter in the course of its life. Stray magnetic fields in any space in which a permanent magnet is likely to be used do not usually amount to more than a few units, and perhaps as good a rule as any would be to make permanent magnets immune to any fields not exceeding 10 units* in all cases where constancy of permanent magnetism is essential. In the typical example of a tungsten steel magnet, to which Fig. 35 relates, immunity from stray magnetic fields of 10 units involves a sacrifice of 7·5 per cent of the maximum possible strength, or 11·9 per cent if the immunity figure is raised to 15 units. In a magnet made of cobalt steel the same immunity would only involve a sacrifice of strength amounting to about one quarter of those percentage figures.

(27) MAGNETIC STABILITY: RESISTANCE TO VIBRATION.

Stray magnetic fields having been guarded against, it remains to consider the effect of vibration on the delicately poised magnetic molecules when they are in the sensitive state of orientation which follows magnetization. Each molecule is a body of definite mass, and owing to the inertia arising from their mass, the molecules will be liable to disturbance by any kind of vibration, whether that associated with temperature or the less regular vibrational motions due to mechanical shock. Hence the molecules in any oriented group which happens to be on the verge of instability could not be expected to withstand energetic vibration, and whether we set them in stronger vibration by raising the temperature or joggle them by dropping the magnet on the floor, it seems certain that the result will be the same: the group of oriented molecules, already at the end of their tether, must inevitably return to the primitive condition of a closed magnetic circuit. The same thing will be likely to happen to oriented groups which possess a small margin of stability, provided the mechanical

* The strength of the magnetic field 20 cm (8 in.) from a long straight conductor carrying a current of 1 000 amperes is 10 units.

disturbance is sufficiently energetic. So far as Ewing's theory holds the truth, all this may safely be predicted, and experiment amply justifies the prediction. If a permanent magnet which has just been magnetized is struck by any kind of non-magnetic hammer or dropped on the floor, it is found that the flux density decreases by a measurable amount. After the jolting of unstable groups back into the primitive state, the magnetic mechanism only contains oriented groups which have some power of self-preservation, and hence the violent mechanical disturbance, if continued, should have less and less effect. This again, is borne out by experiment, for the first few blows have the most effect. The author has found that when a tungsten steel magnet, which had just been magnetized, was dropped repeatedly on the floor, making it ring with a clear musical note, the first 20 blows reduced the initial remanent flux density by 2·75 per cent, but it needed 180 additional blows to increase the loss by 2·15 per cent, the total loss after 200

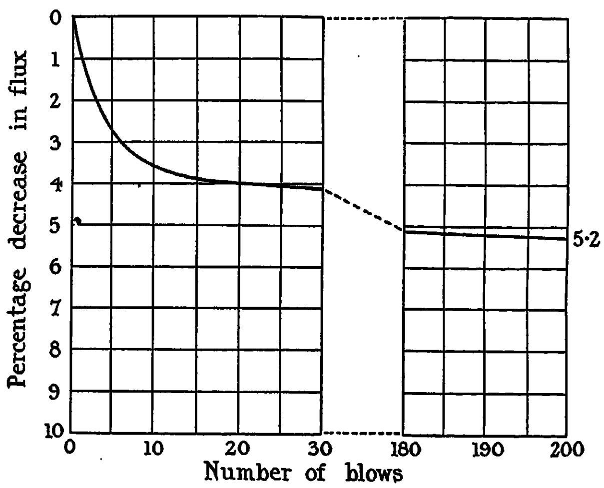

FIG. 37.—Effect of mechanical vibration in reducing the magnetization (orientation of the magnetic molecules) in a permanent magnet of cobalt steel. (Honda.)

blows being 4·9 per cent. In the end, after striking the magnet several thousand times with a brass hammer it appeared that a limit had been reached to what could be done by mechanical vibration of the kind, the magnet having lost, altogether, 5·5 per cent of the initial remanent flux density.

A similar experiment has been recorded by Prof. Honda as an example of the decrease in the flux density of a cobalt steel magnet caused by mechanical disturbance.* From this experiment (illustrated in Fig. 37) it appears that when the magnet was dropped on a wood floor from a height of 1 metre, the first 20 blows effected a reduction of 4 per cent in the flux density. After 200 similar blows the loss had increased to a maximum of 5·2 per cent, a figure not very different from that obtained by the present writer from tungsten steel. But the rough conditions of such experiments as these hardly justify a numerical comparison, and it must suffice to record the fact that in both tungsten magnet steel and cobalt magnet steel, violent disturbance by mechanical vibration or shock causes an immediate reduction of between 5 and 6 per cent in the flux density. Whether the loss of orientation, and therefore of flux density, would be increased if the vibration were continued for an indefinitely long time is a matter of considerable uncertainty and it does not appear that any investigation under stringent conditions has been attempted.

* HONDA and SEIZÔ SAITÔ: "On K.S. magnet steel," *Science Reports of the Tohoku Imperial University* (Japan), 1920, vol. 9, No. 5.

Returning to our tungsten steel magnet, we shall suppose it to have been fully magnetized once more and that the magnetization has settled down again at the natural point of arrest. To impart stability involves the return of a number of the more unstable oriented groups to the primitive state, and we are now acquainted with two ways of doing this. It can be done by the application of a coil field in the adverse direction, or by dropping the magnet on the floor and so jerking the weaker groups into the primitive state. The question now arises whether these two methods are identical in their effect; whether in causing oriented groups to return to the primitive state, mechanical vibration gets hold of the same groups as those whose balance is upset by an adverse coil field. Since in either case the groups with little or no margin will be the first to lose their balance, the probability is that mechanical action and action by adverse magnetic field are, in some measure, alternative ways of doing the same thing. That they are so to a considerable extent, is shown by the following simple experiment.

An ellipsoid bar magnet of tungsten steel having been fully magnetized, the remanent flux density was measured by magnetometer and found to be 7 310. The magnet was next subjected to mechanical vibration by giving it 500 blows in a way capable of repetition. The effect was to decrease the flux density to 7 010, a fall of 300 units. The magnet was now fully magnetized again and the remanent flux density was observed to be 7 310 as before. The next step was to bring the magnetization into a state of recoil by the application and removal of an adverse magnetic field, the strength of the adverse field being 7 units. After recoil from the arrest point determined by the adverse coil field, the remanent flux density proved to be 6 890. In this state of recoil the magnet was of course immune to stray magnetic fields of any value not exceeding 7 units, and the question to be answered was whether the magnet was also immune to vibration. To determine the point the magnet was again subjected to mechanical vibration by giving it 500 blows of the same energy as those given in the preliminary test. The result was to diminish the flux density from 6 890 to 6 830, a fall of 60 units.

The experiment shows that the effect of a particular course of mechanical vibration, which caused a loss of 300 units when nothing had been done to give the magnet stability, caused a loss of only 60 units when a small margin of stability had been imparted to the magnet by means of an adverse field. In other words, when the magnet was in a state of recoil following the application of a negative coil field of 7 units the sensitiveness of the oriented mass of molecules to mechanical vibration was only one-fifth of what it was in the untreated magnet. To that partial extent, therefore, the method of the adverse magnetic field gave immunity to

mechanical vibration, and there can hardly be a doubt that a negative coil field of greater strength would have resulted in a larger degree of immunity to vibration. It is hoped to obtain a numerical relation between strength of adverse magnetic field and immunity from vibration by imparting vibrational energy to the magnet in a regular and measurable form.

The questions which arise with regard to the effect of heat vibrations are identical with those already raised in connection with mechanical vibration. The vibrational effect of heat on the remanent flux density of a magnet is illustrated by the two experiments recorded in Figs. 38 and 39. For these experiments two tungsten

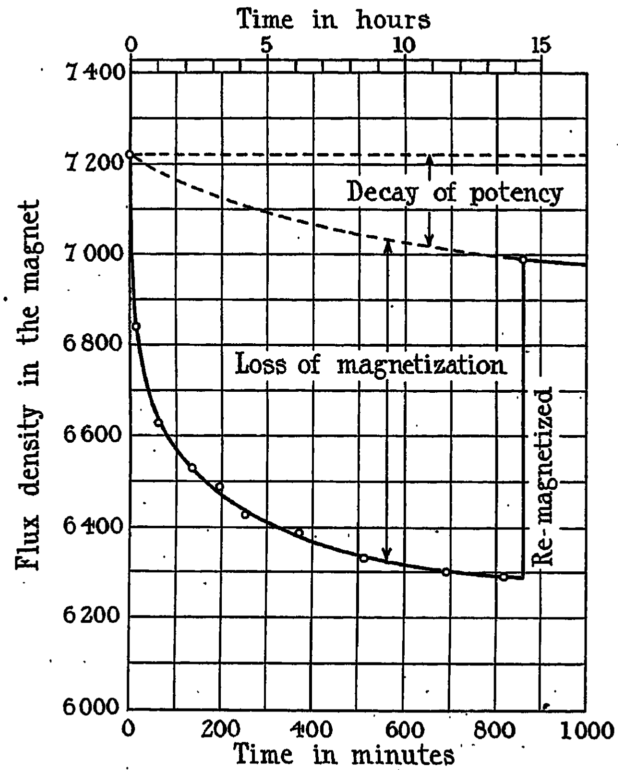

FIG. 38.—Effect of heat vibrations in reducing the magnetization or orientation in a permanent magnet of tungsten steel.

steel magnets were chosen which had not been subjected to any heat treatment since they were hardened. The two magnets were nearly identical in their magnetic characteristics, having been made from the same specimen of steel. In the first experiment, the magnet, after being fully magnetized, had a remanent flux density of 7 220. After making this measurement the magnet was heated to 100° C. for successive periods of time, amounting altogether to 13·7 hours. At the end of each period the magnet was allowed to cool down in order to measure the flux density at room temperature. During the prolonged heating, decay of potency occurred to a noticeable extent, and to ascertain what effect it had on the flux density the magnet was fully magnetized again at the conclusion of the experiment. The total reduction in flux density resulting from 13·7 hours at 100° C. was 930 units, of which 230 were due to decay in the steel. The balance of 700 units is therefore the loss to be attributed to the vibrational effect of the heating on the oriented mass of molecules.

The magnet used in the second experiment had a remanent flux density of 7 130 after being fully magnetized. The first step was to give the magnet a margin of stability, this being done by several temporary applications of an adverse coil field of 18 units. Upon recoil after this treatment the flux density was 6 345. In this condition the magnet was heated to 100° C. for successive periods amounting altogether to 13·4 hours, measurements of flux density being made as in the previous experiment. The total loss of flux density

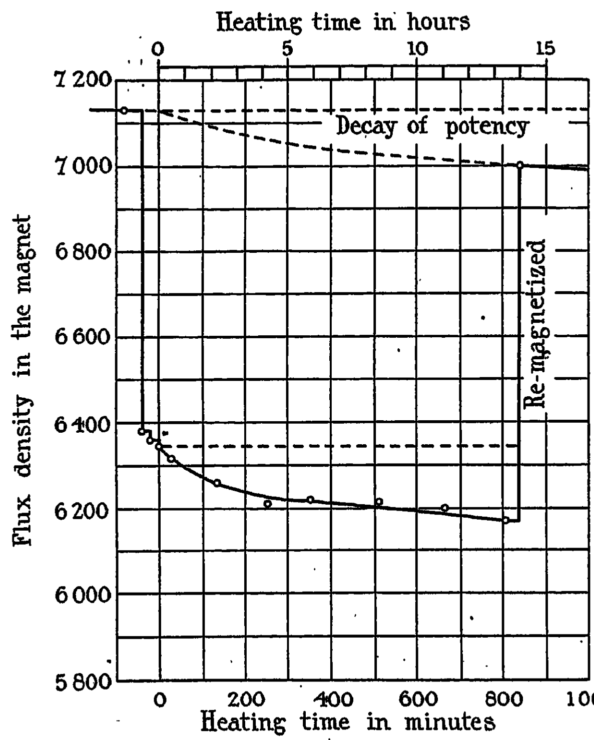

FIG. 39.—Effect of heat vibrations on a permanent magnet of tungsten steel which had previously been given a margin of stability by the application of an adverse coil field of 18 units.

caused by the heating was 185 units, and re-magnetization of the magnet showed that of this amount 130 units was due to decay in the steel. The balance of 45 units is attributable to the vibrational effect of the heating, and comparing this with the 700 units lost from the same cause in the first experiment, it is evident that when the oriented mass of magnetic molecules has been given a margin of stability by means of an adverse magnetic field it is very largely immune to heat vibrations. The immunity is far greater than it was in the case of mechanical vibration. But this is probably to be explained by the greater strength of the adverse field used in the heat experiment, 18 units compared with 7 units in the experiment with mechanical vibration. To obtain a just comparison between the effects of heat vibrations and mechanical vibrations it would be

necessary to make a somewhat elaborate investigation under rigid conditions.*

Much remains to be done to provide conclusive answers to the questions involved in the ageing and stability of a permanent magnet. Once it is recognized that hardened magnet steel suffers a gradual decay, ageing in the strict sense becomes a comparatively simple matter; what is needed is a better knowledge of the rates of decay at different temperatures. Stability of orientation is a more difficult subject, and, although the facts adduced in the present section throw some light on the behaviour of the oriented magnetic molecules in a permanent magnet under different forms of vibration, it still remains doubtful how far the state of recoil, which gives immunity so far as stray magnetic fields are concerned, renders a magnet immune to vibration. Whether in the absence of other disturbing influences, prolonged vibration by heat or by mechanical means has a cumulative effect, is another doubtful matter which could only be cleared up by long-continued experiment.

(28) Conclusion.

With the treatment which imparts stability to the oriented magnetic molecules, the making of the magnet comes to an end. The previous paper began by presenting a picture of the magnetic mechanism, and now in taking a final view our attention has once more been riveted on the wonder-working magnetic molecules and the fragile nature of the means by which they hold themselves together as an oriented system of magnetomotive forces. That any man should be able to build up so delicate a mechanism and preserve it intact for even five minutes would appear impossible if we did not know that permanent magnets are being made by the hundred every day. Apparently, then, the weaving of the elaborate molecular pattern is a simple business; one which the steelmaker and the magnet maker, between them, have long succeeded in doing in a rough and ready fashion. And until recent years they managed to accomplish the feat with their eyes shut. But their success has been very largely a matter of luck. It so happened that primitive man used carbon for smelting iron ore and, some of the carbon finding its way into the iron, steel was produced—by accident. A truly astonishing stroke of luck for the human race, a fortunate chance to which the industry of steel making owes its very existence. If any other element than carbon had been available as the natural fuel for smelting, mankind might well have had to wait for the metallurgical chemist to discover how to make steel for hard tools and permanent magnets. However, by chance the fuel was carbon and the benefit to civilized man—and steelmakers—has been past all reckoning.

Nature provides magnetic molecules of iron ready made. Primitive man introduced carbon by accident. With these two essentials already there the permanent magnet almost makes itself. Nowadays there is no great difficulty in melting scrap steel and improving it with a handful of ferro-tungsten and a pinch of carbon; in casting the molten metal, in hardening it and, finally, in magnetizing it. The product is bound to be a permanent magnet of some sort, good or bad. But the manufacture of uniformly powerful magnets is a very different problem, and it would be hard to find any similar industry so full of pitfalls for the unwary. At every stage from the molten metal to the final treatment for magnetic stability, difficulties crop up one after the other.

The trouble begins in the mixing of the ingredients of magnet steel, uniformity of carbon content being apparently difficult to achieve in practice. But the optimum composition of tungsten magnet steel has now been determined, and it may be hoped that some well-equipped research laboratory will undertake the much more difficult task of determining the optimum composition of cobalt magnet steel. The general use of optimum compositions should leave the steelmaker free to concentrate his efforts on uniformity of composition, more particularly with regard to carbon content. The day for tinkering with the proportions, a little more of this ingredient, a little less of that, is definitely over.

Spoiling the steel by decomposition is the next trouble, and a serious one. But the production of spoiled steel can be prevented and the necessary modifications in steelworks practice will no doubt be made. Reluctance to give up old ways may delay the change; but not for long, when magnet makers begin to be unwilling to buy decomposed steel. Cast magnets are almost unspoiled and their introduction will accustom the magnet maker to something better than badly spoiled rolled steel.

Ultraheating is manifestly quite unavoidable. But ultraheated magnet steel is a trap for the unwary magnet maker rather than a serious difficulty. It is easy to restore it to the normal or all-Alpha state.

The hardening of steel for use as permanent magnets presents several drawbacks, cracking and distortion among them. But as a means of securing the solution of enough carbon to give the necessary degree of potency, hardening is at present indispensable. What it does, in effect, is to prevent the carbide molecules from leaving their solution positions when the allotropic change from Beta to Alpha iron takes place. The carbide molecules may be said to be frozen in their solution positions by the sudden lowering of the temperature of the metal to a point at which very little molecular mobility remains. Temporarily, at all events, this method of compelling more carbide molecules to remain in solution than the solvent Alpha iron naturally holds is entirely successful.

But molecular mobility at ordinary room temperatures, although very slight, is not zero. Little by little the carbide, artificially retained in solution, passes from solution to crystal. Year by year the potency decays. Whether decay will ultimately stop at some point short of the passage of the whole of the surplus carbide out of solution, cannot be foretold. All that is known at present is that four years after the hardening there is no sign of arrest in the progress of decay.

By temporarily heating the steel so as to allow a certain proportion of carbide to pass quickly out of solution, it is easy to forestall the natural decay of years. But this treatment only diminishes the rate

* The experiments recorded in Figs. 38 and 39 formed part of a premature attempt to determine the co-efficient of the temperature variation of magnetization. They were made before the discovery of the decay of potency, and it is only recently that they have been found to throw light on the question of immunity from heat vibration.

of decay to some lower value to which in the natural course of events it would have fallen after a certain number of years. It does not appear that anything can be done to put a stop to the decay of hardened steel.

The discovery of a potency-giving molecule which did not suffer decomposition at temperatures attained during the manufacture of magnet steel would be advantageous, but perhaps the greatest improvement it is possible to imagine, in connection with the manufacture of permanent magnets, would be to dispense with the hazardous process of hardening. What is needed is a potency-giving molecule which will dissolve so much more freely in Alpha iron than any of the carbides at present in use, that the necessary potency will be given by a solution which is in equilibrium at ordinary temperatures. No carbide molecule now in use dissolves in Alpha iron in sufficient quantity, but is it impossible to find one that will? Then again, carbon appears to be the only element which is capable of forming a potency-giving molecule; but is there any ground for supposing that it is necessarily the only element that will serve the purpose? For these questions there seems to be only one reply. No one knows what can be done, because no one has tried.

In the event of the discovery of a potency-giving substance freely soluble in Alpha iron, the advantage of doing away with the risky process of hardening will have one drawback. It may be confidently predicted that iron containing in solution the desired quantity of the hypothetical substance will be too hard to machine in any way but grinding; for it can hardly be doubted that potency and hardness both arise from the molecular pattern of solution.

In a more speculative field for discovery there is the possibility that the powerful magnetomotive forces latent in the atoms of the so-called non-magnetic elements may be made available for use in the same way that the magnetism of iron is now used in permanent magnets. Iron itself has long been calling attention, in vain, to the fact that an element can exist in either of two forms, magnetic and non-magnetic, the change from one to the other involving a fundamental reconstruction of the molecule if not the atom. The discovery of the electron and the electrical constitution of matter has opened our eyes and it is now generally recognized that the atom is not the unchangeable entity it was long supposed to be. If iron can be reconstructed why not other elements? Iron can exist at room temperature in either the magnetic or the non-magnetic form; and again why not other elements?

The immediate practical outcome of the conversion of a non-magnetic into a magnetic element may be glanced at. The 26 planetary electrons in the atom of iron, running round their orbits, provide the magnetomotive force used in the permanent magnet of steel. If only it were possible to induce the 50 planetary electrons in the atom of tin, for example, or better still the 82 in the atom of lead, to behave in the same way as the electrons of the iron atom, we should have a magnetic mechanism of two or three times the magnetomotive force of iron, and where the permanent magnet based on the iron atom maintains a working flux density of 7 000, the magnet of tin would give 13 500, and with the reconstructed atom of lead as the basis of the magnet, a working flux density of 22 000 would be attained. A good deal could be done with such magnets as these.

Whether or no the future holds in store any such revolutionary discoveries in permanent magnetism, we have in the meantime to make the best of the permanent magnet as we know it. An attempt has been made in the present paper to look inside the steel and follow the progress of the molecules as they arrange themselves in the pattern of solution that gives a permanent magnet its power. After much discussion following on a lengthy experimental investigation, and the discovery of more than one troublesome metallurgical fact, we have at last managed to complete the making of what is called a permanent magnet. Beginning with the molecule of iron with its electrons travelling round their planetary orbits, the magnetic machine has been put together molecule by molecule. To obtain the molecular pattern that gives potency it has been necessary to support the mechanism by introducing certain molecules containing carbon—molecules which when in solution appear to behave like props retaining the magnetic mechanism in the required form. Having accomplished this with success, we become aware of the awkward fact that the carbide molecules do not stay where we put them. One after another they drift away from the positions of solution, and how to stop them we do not know.

Looking back on all this and seeing the elaborate molecular pattern slowly falling to pieces, it is only natural that the word permanent, as applied to the magnet of hardened steel, should lose something of its force. But after all, even permanence is relative. It may be said that a permanent magnet is nothing apart from the man who makes use of it, and from that point of view perhaps it is enough that the magnet should be rather more permanent than the man. Anyone who needs greater permanence than that must be content with a magnet made of steel in the softened state. In that condition the steel is a solution in stable equilibrium and the potency is therefore everlasting. But for a given amount of useful magnetic energy, the volume of the magnet would be more than three times that of the hardened steel magnet, and there would be the further drawback that a magnet of softened steel is very easily demagnetized by stray magnetic fields.

So matters stand to-day. But the field of metallurgical discovery is still largely unexplored, and hidden away somewhere the material for the permanent magnet of the future may be waiting to be unearthed. It is already possible to foresee its essential characteristics. It will be endowed with great inherent magnetomotive force and a high degree of potency, imparted by the pattern of solution. Above all, it will be a solution in stable equilibrium, a permanent mechanism for a permanent magnet.

APPENDIX.

ULTRAHEATED MAGNET STEEL.

When steel containing tungsten or chromium, or some other foreign element of the kind, is heated to a high temperature beyond a certain critical point, it undergoes strange modifications in structure which affect the properties of the metal in remarkable ways. In tungsten steels the changes in molecular structure have formed the subject of a prolonged research by Honda and Murakami,* who have based their metallurgical conclusions on the varied forms assumed by the curves which represent the recovery of magnetism as the steel specimen cools down. Setting aside magnetic phenomena, the peculiar properties of high-speed tool steels have frequently been investigated by metallurgists; so far without arriving at a consensus of opinion as to the nature of the changes brought about by the high-temperature treatment. But, although a good deal of exploration has already been done, the fact that magnet steel which has undergone the high-temperature treatment makes a weak magnet, seems to have remained unnoticed until it forced itself on the attention of the present writer while this paper was in preparation.

To make a good magnet out of tungsten steel or cobalt steel, the metal must be in the normal condition in which all the solvent iron is of the magnetic or Alpha variety. But these steels, even at ordinary room temperatures, are often in a peculiar condition in which some of the solvent iron is non-magnetic, and, to the extent that the iron is non-magnetic, the steel is deficient in the inherent magnetomotive force which is essential for a permanent magnet. It is proposed first to consider the circumstances that give rise to this unwanted state of things, and then, after investigating the conditions which determine whether iron molecules are held in the non-magnetic state or revert to their magnetic form, we shall go on to ascertain what is to be done to convert the abnormal steel into the wholly magnetic or all-Alpha state. When non-magnetic iron is present in steel at room temperature, it is often a matter of uncertainty whether it is of the Beta or the Gamma kind, but for the present purpose the point is of no consequence, and for simplicity of statement non-magnetic iron will be referred to as Gamma iron.

It has long been known from the researches of Osmond, Böhler and others, that when steel containing tungsten is heated to any temperature above a certain point in the neighbourhood of 1 100° C., a remarkable change takes place which manifests itself in the subsequent behaviour of the steel. Having undergone some occult change the steel is, temporarily at all events, in an abnormal state, indicated by the much lower temperatures at which the allotropic changes take place when the steel cools down, and by other significant departures from the normal behaviour. It does not appear that any distinctive term has been suggested for this effect, but a word seems to be needed if only to avoid circumlocution. Since the peculiar condition is brought about by heating the steel beyond a certain boundary temperature, it will be appropriate to refer to it as the *ultraheated* state.

The ultraheating effect appears to be entirely absent in plain carbon steel. It is, however, by no means confined to tungsten steel, for it occurs also in steels containing chromium and other kindred elements. In the so-called high-speed tool steels, which often contain both chromium and tungsten in addition to the dominant element carbon, the ultraheating effect is very greatly enhanced—so much so that nearly all the solvent iron remains in the Gamma state when the steel cools down, and consequently all the carbide compounds are retained in solution without the necessity for the hazardous process of sudden cooling by quenching. Moreover, the solvent iron persists in the Gamma state even when the temperature of the steel is raised as high as 500 or 600° C., and so long as it is in that state the carbon remains in solution. It is this natural and persistent state of solution which gives to steels of the high-speed type the immensely valuable property of retaining their hardness notwithstanding the great heat generated by rapid cutting. The extensive use of high-speed tool steels has naturally led metallurgists to attend to the mechanical rather than the magnetic properties of ultraheated steel, but in what follows the phenomena of ultraheating will be described from the magnetic standpoint.

The temperatures recorded by different observers, for the boundary above which ultraheating takes place in tungsten steel, are not very consistent, but they indicate a point somewhere between 1 060 and 1 100° C. The ultraheating effect is known to be accompanied by a considerable absorption of energy, and consequently the boundary temperature may be ascertained by any of the methods employed for detecting changes in the normal rate of heating. For example, the boundary is sharply indicated for tungsten magnet steel in the inverse-rate heating curve shown in Fig. 40. This curve was obtained for the author by Mr. Rolfe from a specimen of magnet steel containing about 0·70 per cent of carbon and 5 per cent of tungsten. It will be noticed that at a point on the temperature scale where the figures given above would lead us to expect the ultraheating effect to begin, there is a sudden and very marked retardation in the rate of heating. It begins sharply at 1 073° C., and comes to an end somewhere between 1 085 and 1 091° C., the magnitude of the departure from the normal course indicating a very rapid absorption of energy. This extremely sudden and active stage quickly comes to an end. It is followed by a retardation of much smaller amplitude which continues for awhile and comes to an end at about 1 215° C., having lasted about ten minutes.

The very sudden absorption of energy, beginning at 1 073° C., must arise from some nearly instantaneous action, and strongly suggests the occurrence of some kind of rearrangement in the structure of atoms or molecules. The subsequent and much less rapid absorption of energy went on for many minutes, and on the view taken in this paper, a duration measured by minutes is a clear indication of changes which involve molecular journeys from place to place. The inverse-rate curve seems, therefore, to point to some instan-

* HONDA and MURAKAMI: "On the structure of Tungsten Steels, *Science Reports of the Tohoku Imperial University* (Japan), 1918; vol. 6, No. 5 (April).

taneous transformation of atoms or molecules, followed by consequential and relatively slow rearrangements of the molecular pattern. It is probable that the entire process of ultraheating would take place at a temperature just above the boundary at 1 073° C., provided enough time were given for the slow consequential changes to be carried to completion. This deduction is confirmed by experimental records drawn from various sources. In some cases ultraheating appears to have been completely effected at temperatures not exceeding 1 100° C. In other instances where the steel was carried to a higher temperature it seems probable that the full development of the ultraheated state was not caused by the higher temperature itself, but was due to the time occupied in raising the temperature. Again, in one of the author's experiments, a specimen of tungsten

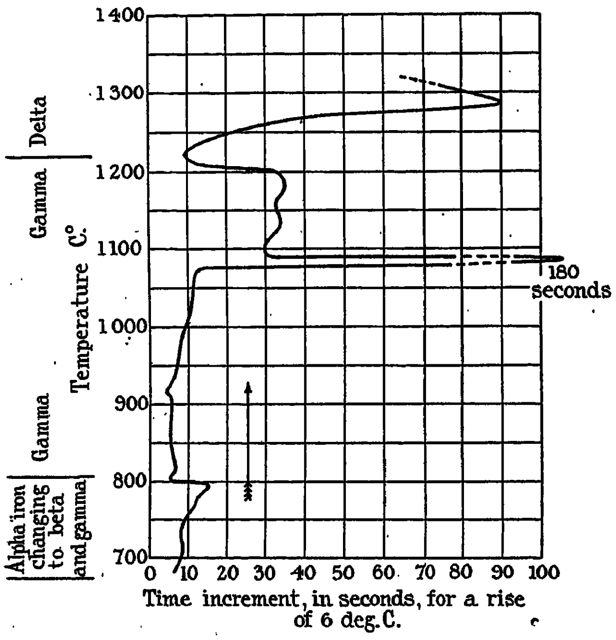

FIG. 40.—Inverse-rate heating curve obtained from a typical specimen of tungsten magnet steel. (R. Rolfe.)

magnet steel which had been rapidly heated to 1 300° C. and then allowed to cool down, was found to be only partially ultraheated notwithstanding the very high maximum temperature. This experiment was made before discovering the importance of allowing ample time for the development of ultraheating, and the temperature of the steel was raised to 1 300° C. as quickly as possible. It was not realized at the time that the rate of heating was excessive, and the significance of the experiment was not understood. But a comparison of the experiment with the inverse-rate curve in Fig. 40 suggests a ready explanation of the fact that the ultraheated state was not fully developed. The inverse-rate curve indicates that ultraheating takes place within a temperature range extending from 1 073 to 1 215° C., and that full development occupies about 10 minutes. Now it appears from an examination of the record of the author's experiment that in heating the steel to 1 300° C., the range from 1 073 to 1 215° C. was traversed in about 3 minutes, and this being less than one-third of the time required for full development, namely about 10 minutes, the partially ultraheated state of the steel at the conclusion of the experiment is well accounted for. Further experiments on ultraheating, paying particular attention to the time element, would doubtless explain many of the discrepancies in existing experimental records.

So much for the thermal conditions that give rise to the ultraheated state. The immediate consequence of ultraheating is shown in Fig. 41. This diagram has been prepared by integrating an inverse-rate cooling curve which Mr. Rolfe had obtained from a specimen of tungsten magnet steel. The steel was cooling down from a temperature of 1 300° C. and as the result of the high temperature it had of course acquired the ultraheated condition.

In the diagram, the lower curve gives the departure from the normal rate of cooling, the amplitude of departure being measured in degrees per minute. The upper curve gives the rate of change of magnetic intensity, or in other words the rate at which the iron in the steel was being transformed into the Alpha variety.* In addition to the time scale, a scale of temperature is included in Fig. 41, and since no recalescence occurred during the cooling of the steel, the scale is continuous although necessarily uneven.

Looking at the two curves in Fig. 41 it will be seen that a small quantity of Alpha iron made its appearance at about the normal temperature in the neighbourhood of 760° C., a transformation which was accompanied by a correspondingly small release of energy. The major portion of the transformation, however, did not begin until the temperature had fallen to 560° C., and the conversion into Alpha iron only ended when the temperature had fallen to 390° C. Turning to the departure curve, it will be noticed that the passing of the carbides from solution to crystal only began at about 460° C. and proceeded so slowly that the temperature had fallen to 180° C. before the whole of the available surplus quantity of carbide had crystallized out of solution.

Comparing this diagram with Fig. 12, which relates to tungsten magnet steel in the normal state, we see at once how great is the contrast between steel in the normal state and ultraheated steel. As the result of ultraheating there is, first of all, a general and very pronounced lowering of the temperatures at which the several allotropic transformations occur, and those at which the process of crystallization begins and ends. In this lowering of temperature there is something that inevitably brings to mind the state of things in an undercooled solution, but steel contains so many unfathomed mysteries that it is perhaps better not to rely on ideas derived from the behaviour of the less complicated liquid solutions.

Another respect in which ultraheated steel obviously differs from normal steel, is in the time occupied by the process of crystallization. Again comparing Fig. 41

* The upper curve in Fig. 41 was obtained from a specimen of tungsten magnet steel of nearly the same composition as that to which the departure curve relates. But unlike the graphs given in Fig. 7 and Fig. 12, the departure curve and magnetic curve in Fig. 41 do not actually record concurrent observations.

with Fig. 12, we see that when the steel is in the normal state the whole of the surplus carbide was able to pass from solution to crystal in a couple of minutes, whereas in the ultraheated condition the same process occupied more than 40 minutes. The longer duration is, of course, the natural consequence of the largely decreased molecular mobility throughout the lower range of temperature within which the passing of the carbide from solution to crystal takes place when the steel is ultraheated.

The general lowering of significant temperatures in ultraheated steel being a very noticeable effect, the boundary temperature above which the ultraheated condition is acquired is often called the "lowering temperature," a term introduced by Dr. Swinden.

If ultraheating did nothing more than lower the temperature range within which the change from solution to crystal takes place, the effect would be as useful in making magnets as it is in making cutting tools; because it would enable the hardening of a magnet to be carried out at a much lower temperature and consequently with less risk of cracking and distortion. But at this point the cutting tool and the magnet part company. For the purpose of a tool, hardness is the main thing, and it is advantageous to retain the solvent iron in the Gamma state, because the amount of carbon necessary for hardness is then held naturally in solution and the risky process of hardening by quenching can be dispensed with: the fact that Gamma iron is non-magnetic is immaterial. But the case of the magnet is very different. Although it is as important in the magnet as it is in the tool to have all the carbon in solution, the presence of non-magnetic iron robs the steel of some of its magnetomotive force and hence, in the magnet, Gamma iron must be avoided.

Now, when tungsten magnet steel—and cobalt magnet steel too, for that matter—cools down to room temperature after being ultraheated, a sensible fraction of the iron does in fact remain in the Gamma state. It is easy to overlook this failure to return to the all-Alpha state, for there is nothing in such experiments as those recorded in Fig. 41, for example, to suggest that the whole of the iron had not been converted into the Alpha variety. But the effect is noticeable, as a deficiency of magnetism, in nearly all curves representing the recovery of magnetism in tungsten magnet steels which have been ultraheated. The author's attention was drawn to the deficiency of magnetism in ultraheated magnet steel by what, at first sight, appeared to be errors of observation in certain determinations of the loss and recovery of magnetism which were undertaken for the present paper, and it was only after examining a number of experimental records that the apparent discrepancies were traced to the effect of ultraheating.

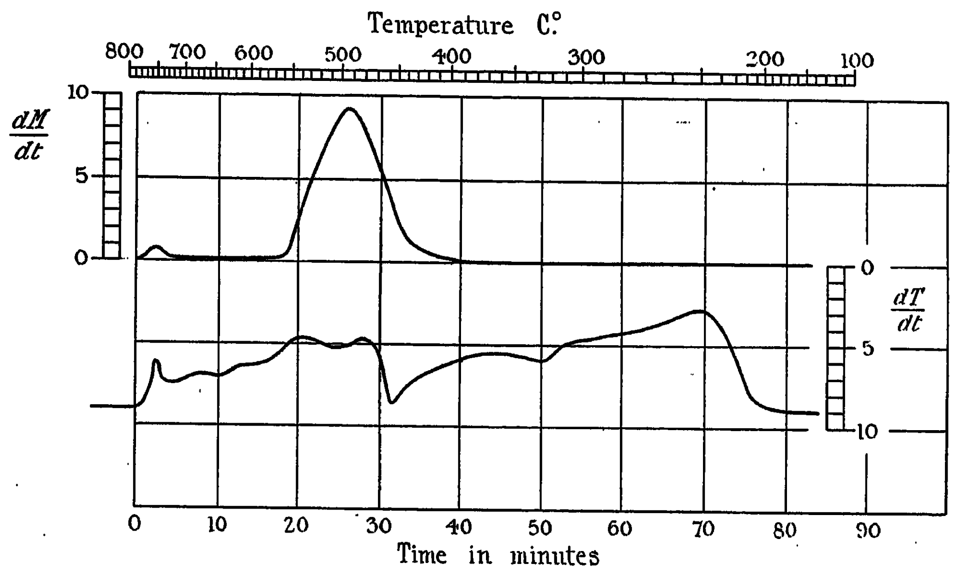

FIG. 41.—Tungsten magnet steel cooling from 1 300° C. Curves showing the rate of change of magnetic intensity during the recovery of magnetism, and departure from the normal rate of cooling consequent on the release of energy as heat.

Finally, the whole matter was made clear by plotting a sequence of curves connecting inherent magnetism with temperature as tungsten magnet steel passed from the normal to the ultraheated state, and back again to the normal condition. These curves are reproduced in Fig. 42, where the vertical ordinates give the percentage of inherent magnetism, or percentage of Alpha iron in a given volume of steel, pure iron at room temperature being represented by 100. The steel to which the curves relate contained 6 per cent of tungsten, 0·65 per cent of carbon, and alien elements 0·70 per cent.

Following the events recorded in Fig. 42, the sequence begins with curve A, which represents the loss of magnetism in a test-piece which was apparently in the normal state, the initial reading at 17° C. being 94·2. The curve follows the usual course, loss of magnetism being practically complete at 800° C., the ordinary temperature for tungsten steel.

Curve B shows the recovery of magnetism in the

same steel, when the test-piece, having been heated to 1 300° C., was allowed to cool down to room temperature. As the result of the ultraheating, recovery does not begin until the steel has cooled down to 600° C.; the transformation into Alpha iron going on at the greatest rate round about 500° C., at which point the difference of temperature between the loss of magnetism on heating and its recovery on cooling is no less than 260° C. Recovery continues as the temperature falls, but it will be noticed that it is still incomplete when the steel has become cold, the inherent magnetism at room temperature being now only 85·2 compared with the initial value of 94·2. The deficiency is roughly 10 per cent and points to the presence of about that percentage of Gamma iron.

Curve C shows the loss of magnetism when the test-piece was heated above the point where the iron loses its magnetism. The curve begins by following the course it continued along some such path as that indicated by the dotted line, and in that case the deficiency of inherent magnetism would evidently have been much the same as it was when the test-piece cooled down from 1 300° C. The actual course of events, however, was very different. Following curve D as the temperature falls, it will be seen that at 600° C. a sudden change took place in the direction of curvature, the curve bending upwards at N and following a course which ultimately brought it close to the normal curve A. The inference seems to be that at 600° C. the deficiency in Alpha iron suddenly began to be made good, the undoing of the mischief wrought by ultraheating making such progress that by the time the temperature had fallen to 200° C. the inherent magnetism or percentage of Alpha iron had risen to 92·7. Observation stopped at this point, but the experiment had been carried far enough to demonstrate the magnetic effects of ultraheating in a general

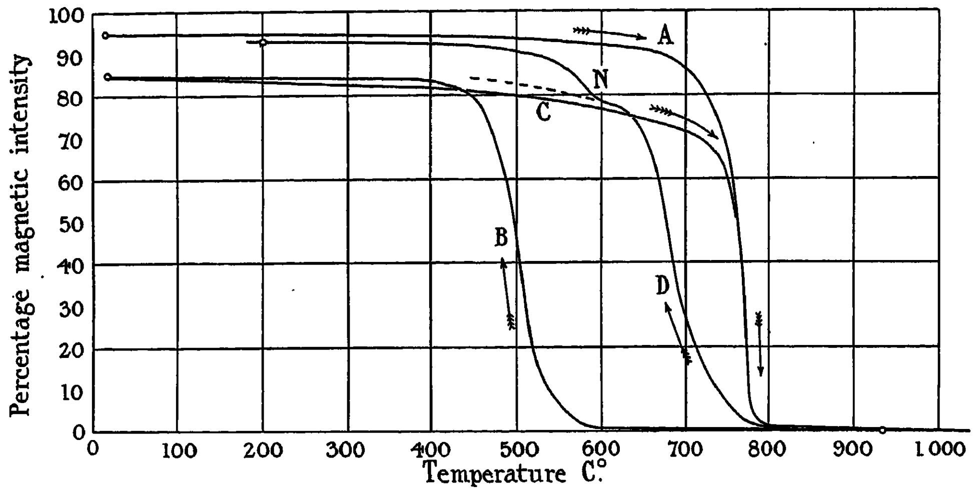

FIG. 42.—A sequence of curves of loss and recovery of magnetism in tungsten magnet steel:—

A. The steel in the normal state. Temperature rising to 1 300° C.
B. The temperature falling from 1 300°; the steel in the ultraheated state.
C. The steel in the ultraheated state; the temperature rising to 935°.
D. The temperature falling from 935°; ultraheating partially cured.

would be expected to take, that is to say it runs more or less parallel with curve A and roughly 10 per cent below it. At about 750° C. curve C makes a near approach to curve A and as the temperature rises above that point the two curves follow the same course, the magnetism vanishing at 800° C. The heating of the test-piece was stopped at 900° C. in order to avoid entering or even approaching the region of ultraheating.

The temperature having reached a maximum of 935° C., the steel was allowed to cool down again, the recovery of magnetism being shown in curve D. In this curve magnetism begins to appear at about 800° C., the effect of ultraheating in lowering the temperature at which the iron begins to change into Alpha having disappeared. But although recovery of magnetism appears to go on much as it would do in normal magnet steel, the influence of ultraheating has not entirely gone. The course taken by curve D as the temperature falls from 650 to 600° C. suggests that it might have way, and to show that the ultraheated state is not permanent. Whatever that state may be—whatever ultraheating actually does to the steel—it can evidently be undone by appropriate heat treatment.

The experiments recorded in Fig. 42 were intended to demonstrate the lowering of the temperature of the magnetic change in ultraheated steel and, as it happened, the conditions were unfavourable for the development of the maximum deficiency of magnetism, the steel having been too rapidly heated to 1 300° C. Moreover, the subsequent cooling from 935° C. was carried out at a speed which afforded barely enough time for the steel to return to the all-Alpha state. The rate of cooling from 750° C. down to 600° C. was about 26 degrees a minute, and the fact that the making good of the magnetic deficiency occurred as a separate event, after the greater part of the magnetic recovery had been completed, suggests that cooling at any greater speed might have resulted in total failure to recover from the effect of ultraheating. The point is one of

importance in practice, and when magnet steel is heated and cooled to remove the effects of ultraheating, the cooling speed may well be limited to something considerably less than 26 degrees a minute in order to avoid the chance of failure.

A deficiency of inherent magnetism in ultraheated tungsten steel is disclosed in several of the author's experiments, the proportion of Gamma iron, as indicated by magnetic deficiency, varying from 8 per cent to 11 per cent. But the experiments were limited in scope and there was nothing to show whether the ultraheated condition had been fully developed or not. Hence the experimental data do not afford a basis for the determination of the maximum possible proportion of Gamma iron in fully ultraheated tungsten magnet steel.

Fortunately the required information can be obtained from the numerous magnetic recovery curves observed by Honda and Murakami. It has already been mentioned that the object in tracing these curves was to determine the molecular constitution of tungsten steels from an examination of the way in which magnetism was recovered as the specimens cooled down. For this purpose it was not thought necessary to take into account the different values of the final intensity of magnetization after the steel had cooled down from different temperatures. Nevertheless each recovery curve was followed down to a final temperature of 50° C., and from the recorded values of the intensity of magnetization at that temperature the present writer has determined the amount of non-magnetic iron present in each ultraheated specimen. None of the 53 tungsten steels examined by Honda and Murakami had the composition of the best tungsten magnet steel, but by a method of interpolation it has been possible to make an accurate computation of the percentage of non-magnetic iron in ultraheated tungsten magnet steel of the composition in common use at the present time. Taking 6 per cent of tungsten and 0·7 per cent of carbon as a typical composition for magnet steel, and supposing the steel to be in the fully ultraheated condition, the author finds that it will contain 16·4 grammes of non-magnetic iron per 100 grammes of solvent iron.

The figure just given shows that if a permanent magnet made of good tungsten magnet steel happened to be in the fully ultraheated state it would be roughly 16 per cent weaker than a similar magnet made of the same steel but in the normal or all-Alpha state. It is hardly possible for the steel to retain the ultraheated condition to the full extent when it comes to the hardening, but ultraheating must often cause permanent magnets to be 10 or 12 per cent weaker than they need be. The weakness arises from the deficiency of magnetic molecules and not from any loss of potency; for, provided the hardening is fully effective, the whole of the carbon in magnet steel will be retained in solution, giving the maximum potency whether the steel is ultraheated or normal.

When magnet steel is in the softened state there is a remarkable difference between the normal and the ultraheated condition; the potency of ultraheated steel in the softened state being much greater than that of the same steel when normal and in the softened state. This unexpected state of things is easily demonstrated by a few measurements of the coercive force of a piece of magnet steel in the softened condition, first after cooling it down from a temperature well above the ultraheating boundary, and then after cooling from a point well below the boundary. Some typical measurements of this kind are given in Table 17. The tabular figures record the results of five tests made one after the other on a piece of ordinary 6 per cent tungsten magnet steel received from the steelworks in the form of rolled bar. Each test was made with the steel in the completely softened state, that is to say, in every case the steel was cooled slowly enough to permit all the surplus carbide which could pass out of solution to do so. It will be noticed that when the steel was in the normal or all-Alpha state the coercive force was 15, a very usual figure for softened tungsten magnet steel; whereas when the same piece of steel was in the ultraheated state the coercive force was 25·8, on an average of three tests, an excess of nearly 11 units. Similar experiments are quite likely to result in figures differing by two or three units from those in the table, but it will always be found that the coercive force of the ultraheated steel is 10 or 11 units greater than that of the same steel in the normal state when both are in the softened condition. It is not uncommon for the coercive force of softened tungsten magnet steel in the fully ultraheated state to be as high as 28 or 29, the latter figure being the highest value of which the author has any record. Taking 26 and 29 as extreme values, a rough average value would be 27·5 units.

TABLE 17.

	Condition of the steel and its heat treatment	Coercive force
a	As received from the rolling mill ..	26·5
b	After heating at 1 130° C. for 5 minutes, followed by slow cooling to 20° C.	25·0
c	After heating at 930° C. for 5 minutes, followed by slow cooling to 20° C...	17·0
d	After heating at 710° C. for 45 minutes, followed by cooling in the air ..	15·0
e	After heating at 1 180° C. for 5 minutes, followed by slow cooling to 20° C.	26·0

(a), (b) and (e) in the ultraheated condition; (c) nearly normal; (d) quite normal.

Coercive force of softened tungsten magnet steel in the ultraheated state, and in the normal or all-Alpha state.

A coercive force of 27·5 in ultraheated tungsten magnet steel, in the softened state, can be accounted for if we suppose that the potency of the steel as a whole depends not solely on the carbon dissolved in the Alpha iron (which alone constitutes the magnetic mechanism), but on the whole amount of carbon in

solution, without distinguishing between what is dissolved in non-magnetic iron and what in magnetic iron. The surplus carbon rejected from solution when the greater part of the solvent iron is transformed into the Alpha variety will naturally dissolve in the surviving Gamma iron which will ultimately become a saturated solution containing 1·02 gramme of carbon per 100 grammes of iron.* Alpha iron will retain about 0·24 gramme of carbon in solution per 100 grammes of iron, and, assuming the ultraheated condition has been fully developed, the solvent iron will be 83·6 per cent Alpha and 16·4 per cent Gamma iron. Hence the quantity of carbon dissolved in the Alpha iron will be $0{\cdot}24 \times 0{\cdot}836$, and in the Gamma iron $1{\cdot}02 \times 0{\cdot}164$. That is to say, the amount of carbon in solution will be about 0·20 gramme in the Alpha iron, plus 0·17 gramme in the Gamma iron, making a total of 0·37 gramme of carbon in solution per 100 grammes of solvent iron. In steel containing 6 per cent of tungsten and 0·70 per cent of carbon, the solvent iron constitutes about 92 per cent of the weight of the steel, and consequently the 0·37 gramme of carbon when reckoned on the weight of steel becomes 0·34 per cent. The steel being supposed to contain 0·70 per cent of carbon, 0·39 per cent would be present as tungsten carbide and 0·31 per cent would be carbide of iron. Assuming the quantity of carbon in solution in the softened steel, namely 0·34 per cent, to be divided between the two carbides in the same proportion, 0·19 per cent must be reckoned as tungsten carbide and 0·15 per cent as carbide of iron. Reading from the carbon-coercive-force curve for 6 per cent tungsten steel (Fig. 9) it will be found that the corresponding items of coercive force arising from these percentages of carbon in solution are 24 units and 3 units respectively. The total coercive force would therefore be 27 units, this being the estimated coercive force of the ultraheated steel when in the softened state.

The estimated value of the coercive force, arrived at in the last paragraph, agrees so closely with the values commonly observed in specimens of ultraheated tungsten magnet steel in the softened state as to leave very little doubt that the total amount of carbon in solution is in fact the governing quantity as regards potency. It seems clear that any carbon dissolved in the magnetically inoperative Gamma iron creates potency in the magnetic mechanism, just as it would do if it were actually in solution in the Alpha iron which constitutes that mechanism. The ability of carbide molecules dissolved in Gamma iron to exert a potency-giving force in neighbouring Alpha iron suggests that it is the solution pressure of the dissolved carbide compounds which gives rise to the potency, a pressure exerted throughout the mass of mingled Alpha and Gamma iron without regard to the precise locality of the solute molecules. But an explanation of this kind does not really carry us very far. The phrase "solution pressure" belongs to the statistical view of solute molecules. It does not tell us anything of the doings of individual molecules, and in the author's view the secret of potency in steel lies in the action of the individual carbide molecule on a small group of magnetic molecules.

The method used above in estimating the coercive force of fully ultraheated magnet steel in the softened state may be employed to compute the coercive force of partially ultraheated steel containing any given proportion of Gamma or non-magnetic iron. Having calculated a number of co-ordinate values they may be used to construct a graph showing the relation between the percentage of Gamma iron in the solvent iron and the coercive force of the steel when in the softened state. A graph of this kind relating to 6 per cent tungsten steel containing 0·70 per cent of carbon is given in Fig. 43.

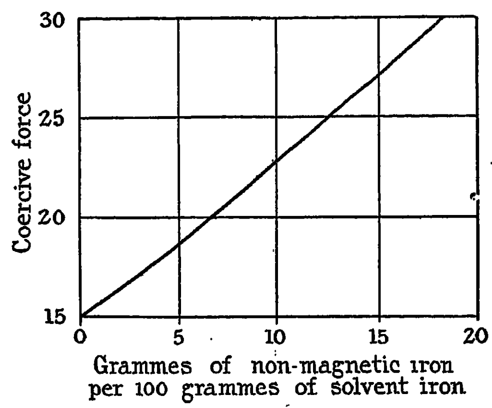

FIG. 43.—Ultraheated tungsten magnet steel in the softened state. Graph giving the relation between the percentage of non-magnetic iron and the coercive force of the softened steel. (Computed by the author.)

Both cobalt steel and tungsten steel are liable to ultraheating, and no matter how magnet steel is made it is inevitably fully ultraheated in course of manufacture. Magnet steel as it comes from the steelworks is therefore always in an ultraheated condition, the deficiency in magnetism varying according to the heat treatment which the steel has undergone since it was ultraheated. A direct measurement of the deficiency in magnetism is not easily made with accuracy, but by measuring the coercive force of the steel when in the softened state and referring to a graph like that given in Fig. 43, the proportion of Gamma or non-magnetic iron present in the steel is seen at a glance. The percentage of non-magnetic iron is the same thing as the deficiency in the inherent magnetism of the steel and, knowing that, the percentage loss of useful magnetic power is determined. It will be seen from Fig. 43 that in the case of tungsten magnet steel tested in the softened state, a coercive force anywhere between 20 and 30 is a sure indication of the presence of a considerable percentage of non-magnetic iron.

Ultraheated magnet steel naturally makes a poor magnet, but fortunately the mischief done by ultra-

* The percentage of carbon in the saturated solution is here assumed to be the same in tungsten magnet steel as it is stated to be in carbon steel. Metallurgical textbooks give 1 atom of carbon to 24 atoms of iron as the eutectoid proportion in carbon steel, but whether this ratio dropped from the sky or was determined by chemical analysis does not appear. Assuming the correctness of the proportion and giving three of the iron atoms to the carbon atom to form Fe_3C, there will be 21 atoms of solvent iron to each carbide molecule. Hence the percentage weight of carbon to solvent iron will be $100 \frac{12 \times 1}{55{\cdot}85 \times 21}$ which is 1·02, the figure used in the text.

heating is not irreparable. It can be undone by suitable heat treatment, and from the point of view of the magnet maker perhaps the most important discovery to make about the ultraheated state is how to get rid of it—how to cure ultraheated steel.

There are several ways of restoring ultraheated steel to the normal state in which all the solvent iron is magnetic. The methods which depend on heat treatment all act in essentially the same way, and the choice between them turns only on what happens to be convenient in practice. A possible alternative to heat treatment is to lower the temperature of the steel to some point, at present undetermined, at which any non-magnetic iron would revert to the magnetic state. So far as permanent magnets are concerned, everything turns on the solvent iron being wholly converted into the magnetic state, and the various ways of removing the effects of ultraheating will be better understood if we begin with an examination of the conditions which bring about the magnetic change when the steel is in the ultraheated state.

In Section (11) it has been shown that the occurrence of the magnetic change at some particular zone of temperature, can be accounted for first by supposing that each iron molecule is constantly urged to assume the magnetic form by a force of reversion which is inherent in the system of electric currents embodied in the molecule, and then by assuming that this inherent force of reversion is opposed by a general pressure acting equally on every molecule of iron throughout the mass. It may be that pressure is not the sole variable force opposing the reversion of non-magnetic iron to the magnetic state, but so far as steel in the normal condition is concerned, pressure appears to be the principal factor on which the magnetic change depends. Apart from hypothesis, there is the outstanding fact that in any kind of steel, provided it is in the normal state, the condition which brings about the magnetic change affects the whole of the solvent iron. Above the temperature zone where the magnetic change occurs, all the iron is non-magnetic; below that zone all the iron is magnetic. Clearly, whatever the nature and origin of the force which determines the magnetic change, it is a force which acts on all iron molecules alike; it is a general and not a selective force.

We now turn to the consideration of the conditions which bring about the magnetic change in ultraheated steel. It will be convenient to take ordinary tungsten magnet steel as our example, since it is the type of steel with which we are concerned in this paper and exhibits all the phenomena of ultraheated steel. Experimental records of the magnetic change in ultraheated tungsten magnet steel have already been given earlier in this Appendix, and there is, in addition, a most valuable fund of information of the same sort to be found in the magnetic recovery curves obtained by Honda and Murakami.* In high-speed tool steels ultraheating is developed to a much greater extent than it ever can be in magnet steels, but these steels do not appear to have been investigated by magnetic methods. So far, thermal evidence alone seems to have been obtained and in the absence of magnetic data the key to ultraheating is missing.

We have seen in Fig. 41 that when tungsten magnet steel cools down from a temperature above the ultraheating boundary, the magnetic change does not take place until the temperature has fallen a long way below the zone where magnetism is regained when the steel is in the normal state. Without further inquiry this lowering of the temperature, at which the solvent iron reverts to the magnetic state, might be attributed to an increase in the pressure; an increase in solution pressure might be supposed to result from some occult molecular change brought about by ultraheating. But we already know that Fig. 41 does not tell the whole story. It omits to record the significant fact, disclosed by recovery curve B in Fig. 42, that when the partially ultraheated steel had cooled down to room temperature 10 per cent of the solvent iron was still in the non-magnetic state, and the magnetic change which ended at 390° C. was therefore limited to the conversion of 90 per cent of the solvent iron from the non-magnetic to the magnetic state. The same limited reversion to the magnetic condition is shown over and over again in the magnetic recovery curves recorded by Honda and Murakami. In the case of tungsten magnet steel which has cooled down to room temperature after being fully ultraheated, about 84 per cent of the solvent iron will be found to have reverted to the magnetic state, leaving 16 per cent still in the non-magnetic and therefore useless form. Here we have clear evidence of the existence of forces of widely different strength, acting selectively on the iron molecules and opposing their inherent tendency to revert to the magnetic state. Out of every 100 molecules, 84 are under the restraint of some individual opposing force in addition to the pressure. These two forces together constitute a total force of restraint which is only finally outweighed by the inherent force of reversion when the temperature has fallen to 390° C. and by so doing greatly reduced the pressure.

The temperature having fallen to 390° C., about 84 per cent of the solvent iron has changed into Alpha iron and a corresponding proportion of surplus carbide is released from solution. The passage of carbide from solution to crystal proceeds as the temperature falls, and by the time the steel has cooled down to room temperature the transfer will be at an end, as the lower curve in Fig. 41 clearly shows. Hence when the steel is cold the pressure will have fallen not only as the result of the fall in temparature, but because a quantity of solute will have passed out of solution, thus making a further reduction in pressure. Taking the diminution in solution pressure into account, it is easy to show that the total pressure at 15° C. must be much less than half what it was at 390° C., yet notwithstanding this great reduction in the general force opposing the reversion of non-magnetic iron to the magnetic state, roughly 16 per cent of the solvent iron is still held in the non-magnetic form. The inference must be that out of every 100 molecules, 16 are under the restraint of some opposing force acting individually on each of them, and that this force is

* The author is indebted to Professor Honda for copies of the three Science Reports relating to the structure of tungsten steels and the characteristic properties of cobalt magnet steel.

of far greater strength than that which opposed the reversion of the 84 molecules.

In ultraheated steel, then, every molecule of solvent iron is acted on by one or the other of two selective forces, in addition to the general pressure which is present in any case, whether the steel is ultraheated or not. The existence of these selective forces may be accounted for by supposing that ultraheating creates bonds between certain of the solute molecules and groups of iron molecules, a binding together by intermolecular forces which may perhaps be akin to chemical union, although the bonds are apparently of a somewhat transient character. But the explanation, which is at present only in a tentative stage, belongs to a remote metallurgical region beyond the scope of this paper. For the immediate purpose it is not necessary to attach metallurgical labels to the two bonds; it is enough to recognize their existence in ultraheated steel, each holding in bondage a definite proportion of the whole quantity of solvent iron and opposing the reversion to the magnetic state. To mark the fact that one bond is much stronger than the other we shall refer to them as the major and minor bonds.

The proportion in which any particle of the solvent iron is divided between the two bonds depends on the composition of the steel and the extent to which it has been ultraheated. In high-speed tool steels containing both tungsten and chromium in additon to carbon, it is possible for the whole of the solvent iron to be under the influence of the major bond, provided the ultraheated state is fully developed. In that condition the steel should of course be non-magnetic at room temperature, but the author is not aware of any evidence on the point. For ordinary tungsten magnet steel in the fully ultraheated state the proportion in which the iron molecules are divided between the two bonds has already been given, 84 molecules out of every 100 being caught, as it were, in the minor bond and 16 in the major bond, these figures being close approximations to the true proportions. Strictly speaking, the proportion 84 to 16 only applies to the state of things existing in the steel when the temperature is above the zone where the magnetic change would occur if the steel were in the normal state. We have already seen that in cooling down to a temperature below 390° C. the minor bond comes undone, and consequently at room temperature the major bond alone survives, holding about 16 per cent of the solvent iron in the non-magnetic state. With the steel in this condition we may once more note the play of forces on each non-magnetic molecule of iron. Since the molecule is non-magnetic the system of electric currents embodied in it is not one of stable equilibrium, and hence there is a constant force urging the molecule to revert to the magnetic state which alone gives it stable equilibrium. Acting in opposition to this inherent force of reversion there is the pressure arising from the temperature, the pressure arising from the presence of solute molecules, and the force of the major bond. At room temperature the sum of these three opposing forces exceeds the force of reversion and consequently the molecule is held in the non-magnetic form. This state of things applies to 16 out of every 100 molecules of solvent iron and robs the steel of 16 per cent of its useful power as a permanent magnet. That in a few words describes the condition of tungsten magnet steel in the fully ultraheated state.

That the magnetic or non-magnetic state of an iron molecule must depend on the preponderance of forces, one way or the other, is of course self-evident, but some sort of working hypothesis, such as that outlined in the foregoing paragraphs, was needed in order to provide a string of coherent ideas. With their aid we proceed to consider the curing of ultraheated steel.

Since the effect of ultraheating is to create bonds which prevent the solvent iron from reverting to the magnetic state, and the magnetic state is essential for permanent magnetism, the most obvious remedy is to sever the bonds, assuming that to be possible. But it would answer the purpose equally well if, leaving the bonds intact, the sum of all the forces opposing the reversion of non-magnetic molecules to their magnetic form could be reduced to the point at which the total opposing force was outweighed by the force of reversion. This is in fact the natural and easy way of disposing of the influence of the minor bond, for the reduction in pressure when the steel cools down to room temperature brings the sum of the opposing forces well below the force of reversion, and consequently by the time the ultraheated steel is cold all the solvent iron caught in the minor bond has already reverted to the magnetic state. To that extent, therefore, the harmful effect of ultraheating on the magnetism of iron is removed by the simple expedient of cooling the steel down to room temperature, and having overcome its influence in the simplest possible way there is no occasion to take further notice of the minor bond.

It remains to deal with the major bond. At room temperature this bond, together with the total pressure, more than balances the reversion force. But since the minor bond has been disposed of by lowering the temperature, and with it the pressure, there is good reason to believe that with a further lowering of temperature a critical point would ultimately be reached at which the greatly reduced pressure, plus the force of the major bond, would be outweighed by the reversion force; at that point, possibly a long way down the scale of temperature, all the iron caught in the major bond—which is as much as to say all the iron remaining in the non-magnetic state—would revert to the magnetic condition. This final transformation having taken place, all the solvent iron would be in the magnetic state and so far as magnetisn is concerned the steel would have assumed the normal or all-Alpha condition. Whether this method of overcoming the major bond by low temperature is practicable depends on whether the critical temperature is within easy reach. The discovery of the harmful effect of ultraheating on magnet steel being of recent date, the author has had no opportunity to determine the whereabouts of the critical point. There should not be much difficulty in finding it, since liquid air boiling at 182 degrees C. below zero is available for experiment.

The alternative to overpowering the ultraheating bonds by lowering the temperature is to get rid of the harmful effect of ultraheating by actually breaking the

bonds. This can be done and by good fortune it only needs heat treatment of a simple kind. In one form the method is already in use by toolmakers as a means of softening high-speed tool steel, though whether the toolmaker clearly understands what is happening to the steel is open to doubt. A hint of what is needed to break the major and minor bonds is to be found in Fig. 41, where the curve which gives the rate of growth of the magnetic intensity clearly shows that non-magnetic iron began to be converted into Alpha iron at about the temperature where the magnetic change would have been in progress if the steel had been in the normal state. This slight reversion to the magnetic condition suggests the possibility that the ultraheating bonds began to break up within that region of temperature, but that something checked the progress of reaction. However, the diagram conveys no more than a hint, and to obtain further light we must once more turn to the magnetic 54 minutes being occupied in traversing the 50 degrees. At 700° C. the cooling speed was restored to the normal rate of 29 degrees a minute.

Looking at curve E, it will be noticed that when the steel cooled down at the high speed of 100 degrees a minute, the final percentage intensity of magnetization at 50° C., practically room temperature, was only 87, showing that 13 per cent of the solvent iron was still under the restraint of the major bond. But curve F shows that at the slower cooling speed of 29 degrees a minute the final percentage intensity rose to 94, indicating that the slower cooling had resulted in the release of 7 per cent of solvent iron from the major bond. From the course taken by the curve below 750 as far as 600° C., it seems that the release took place while the steel was traversing that region of temperature, and if the steel had cooled still more slowly the additional time within that region would have

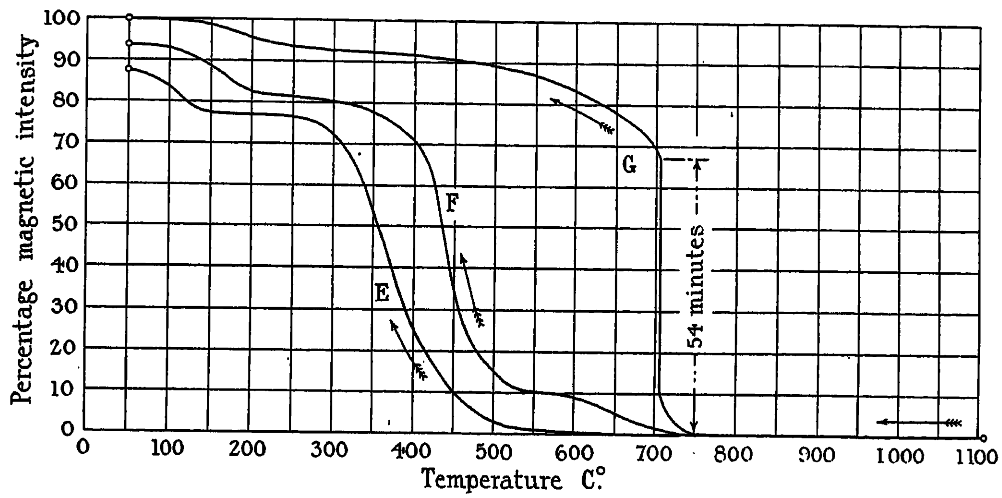

FIG. 44.—Curves showing recovery of magnetism in tungsten magnet steel when cooling from a temperature just above 1 100° C. at different speeds. E at 100 degrees a minute; F at 29 degrees a minute; G at 1 degree a minute. [Honda.]

recovery curves recorded by Honda and Murakami, choosing a set of curves relating to tungsten steel not too widely different from ordinary tungsten magnet steel. Fig. 44 is reproduced from a diagram containing three recovery curves obtained from a specimen of steel containing 7·9 per cent of tungsten and 0·63 per cent of carbon. Each curve is plotted from observations made while the specimen was cooling down from 1 100° C. This temperature being above the ultraheating boundary, the specimen was of course in an ultraheated condition, but it is unlikely that the ultraheated state would be fully developed at a temperature so little above the critical point at 1 073° C. The marked differences between the three curves arise from the widely different rates at which the steel was cooled. In curve E the cooling speed between 700° and 350° C. was 100 degrees a minute. In curve F the same range of temperature was traversed at 29 degrees a minute. In curve G the rate of cooling was intentionally checked at 750° C., and from that point down to 700° C. the cooling was reduced to something like 1 degree a minute, resulted, no doubt, in the release of a greater quantity of solvent iron from the major bond.

That the major bond slowly comes undone just below 750° C., and that the release of the whole of the iron caught in that bond is only a question of time, is clearly shown in curve G. In the course of 54 minutes, the temperature being nearly constant at about 700° C. for most of the time, all the solvent iron was released from the bondage set up by ultraheating, and the recovery of magnetism was complete. To state the fact in another way, the breaking of the ultraheating bonds, which is evidently in progress at about 700° C., goes on so slowly that it needed 54 minutes to complete the undoing and remove the effects of ultraheating. We could hardly have a better example, for these three curves demonstrate all the essential facts. Cool the steel quickly, and the major bond survives intact at room temperature for want of time to come undone while the temperature was traversing the breaking-up region. But if there is enough time within that region for the complete breaking up of the ultraheating bonds,

the whole of the solvent iron will be released from bondage. Since the breaking-up region is just below the temperature zone of the magnetic change in normal steel, the release of non-magnetic iron from either of the ultraheating bonds is, of course, followed immediately by its reversion to the magnetic or Alpha form.

It is clear that whatever heat treatment it may be convenient to use for the purpose, the actual curing of the ultraheated steel will take place only while the temperature is within the region where the ultraheating bonds break up. Assuming that a piece of ultraheated steel has already cooled down to room temperature, the minor bond will have been overcome. To break the major bond, the steel may first be heated to some temperature above the breaking-up region (taking care not to approach the ultraheating boundary) and then immediately allowed to cool down through the breaking-up region. This method is illustrated by curves C and D in Fig. 42. The ultraheated steel having been heated to 935° C. and then cooled down to room temperature, the curves show that about 10 per cent of the solvent iron was released from the major bond during the passage through the breaking-up region, which extends from 750 down to about 600° C. Heating the steel to so high a temperature as 900° C. is, however, quite unnecessary. It would have answered the purpose equally well to raise the temperature to the upper boundary of the breaking-up region (about 750° C. in the case of tungsten magnet steel), and then to allow the steel to cool down slowly.

The severing of bonds, the magnetic change and the consequent passage of carbide from solution to crystal, involves the liberation of a good deal of energy as heat, and unless this heat is removed the temperature of the steel rises and the whole process stops. To keep the process going, therefore, it is necessary that the temperature of the walls of the furnace should be somewhat lower than the temperature of the steel, a condition which involves a falling temperature. With but little difference of temperature between steel and furnace wall the whole process of change goes on extremely slowly, but there is ample time for the complete breaking-up of the ultraheating bonds before the temperature of the steel falls below the breaking-up region. This was the condition under which curve G in Fig. 44 was obtained, and the very slow cooling resulted in the release of 13 per cent of the solvent iron from the major bond. If the steel had been fully ultraheated there would have been rather more than 16 per cent of solvent iron caught in the major bond, and a good deal more time would have been needed to release it. On the other hand, if a greater temperature difference is established between the steel and the furnace wall in order to accelerate the process of change, the temperature of the steel falls more quickly and may pass below the breaking-up region before the breaking up of the major bond has been completed. This was the state of things when curve D in Fig. 42 was obtained, and the cooling, which went on at the rate of about 26 degrees a minute resulted in the release of only 10 per cent of the solvent iron from the major bond. These two examples make it clear that the quantity of solvent iron released from the major bond, as the temperature of the steel falls through the breaking-up region, is largely governed by the cooling speed.

The most generally convenient way of curing ultraheated steel is to heat it to some temperature just above the breaking-up region and then let it cool down through that region at the rate of about 15 degrees a minute. At this speed about 12 per cent of solvent iron will be released from the major bond, and to effect the complete cure of fully ultraheated tungsten magnet steel a repetition of the temperature cycle would be necessary. The only practicable alternative to treatment by two heat cycles is to reduce the cooling speed to such an extent that an hour or more is occupied in lowering the temperature from 750 to 600° C.

Ultraheated cobalt magnet steel has yet to be investigated. Judging from a few scattered observations made in the course of other work, ultraheating has a much greater effect on cobalt steel than it has on tungsten steel. With two solvents, iron and cobalt, mutually soluble in each other, and at least three kinds of solute molecule, including a chromium carbide, it seems probable that more than two kinds of bond would be brought into existence by ultraheating. One of them is likely to prove troublesome, for long before the discovery of cobalt magnet steel there was reason to suspect that the presence of chromium in steel creates an ultraheating bond of an extremely persistent kind.

So far as the curing of ultraheated tungsten magnet steel is concerned we are now out of the wood. Since the phenomena of ultraheating are only to be found in steels which, in addition to carbon, contain tungsten or some element of similar character, it is obvious that under certain conditions solute molecules which contain foreign elements of that kind acquire the power of holding iron molecules in the non-magnetic state. But although it is possible to identify certain types of solute molecule endowed with the power of holding non-magnetic iron molecules in some kind of bondage, the nature of the force exerted, and how it is brought into action by ultraheating are shrouded in mystery.

Discussion before The Institution, 19 March, 1925.

Mr. Ll. B. Atkinson: The present paper is a continuation of a previous paper in which the author dealt with two questions, different but, of course, connected. He dealt with the theory of permanent magnetism and he dealt up to a point with the practical construction of magnets, that is to say, the predetermination of a magnet for a given task. In that paper he took steel, shall we say, in the abstract—steel as he found it—and showed us how with that and its properties, for which he gave a theory, we could predetermine the magnets by methods which he then laid down. The present paper carries us forward a further stage. The author gives a theory not only of the source of the magnetization of steel, but also of all the various defects and faults

which are found in magnet steel. In the previous paper the author put forward his theory of permanent magnets. At that time we were looking on magnetism as something produced in iron by a coil giving a magnetomotive force acting on a medium which had a reluctance or permeance varying with the flux it was carrying, and so a flux was produced. It was the image of an electromotive force acting on a resistance which itself depended on the current being carried. The author took us away from that idea altogether to the idea that the exciting coil was only, as it were, a trigger which set off, by orienting the molecules, something else which was inherent in the iron. Every molecule had a fixed magnetomotive force which acted always on a medium—the ether—of a constant permeance. That was a revolution in thought. It was one, to me at least, not easy at the moment to accept, and I took exception to one or two points. An argument which I raised was the question of the orientation of these molecules, having in view the fact, as it appeared to me, that this permanency or constancy of magnetomotive force was impossible in view of the fact that unless an electromotive force is applied to a circuit of perfect conductivity (which we may assume the electron orbit to be) the electro-kinetic momentum, that is the flux, through that orbit will remain constant. In the author's reply he admitted that there is not absolute constancy of the magnetomotive force, yet pointed out that with reasonable dimensions of the electron orbit and the distances of the molecules, the detectable difference is so small, running into one part in many millions, that for all practical purposes, and for all theoretical purposes with which we are concerned, there is that constant magnetomotive force. No one, I think, can doubt that this paper, with the preceding one, has made the ground perfectly plain as to the procedure necessary to make carbon, tungsten and cobalt magnets with certainty. No one, I think, can doubt after studying this paper that the Ampère-Weber conception of the molecule and the Ewing explanation of the magnetization of iron are in broad principle correct. That the permanency of the magnetic state is due to variform spacing of the molecules is at least a reasonable hypothesis, though I think there are other possible ones. The author suggests that the alteration of iron from the Alpha to the Beta state takes place by the iron molecule being composed of two atoms, that is, containing two electronic orbits, which normally and in a stable condition are lying parallel to one another. He suggests that by some means those two orbits are oriented so that they face one another. The electrons are then revolving in opposite directions and annul one another so far as any magnetomotive force is concerned. He points out that under those conditions those two electronic orbits are not in a stable position. They must be put there by something and held there by something; and he suggests that that something is the kinetic pressure arising from those movements of the iron particles which we call heat, and the kinetic pressure arising from what we call solution pressure. I find it very difficult to form any sort of mental image of how an orientation which is a directive process can be brought about by kinetic pressures which are essentially non-directive. I think that the author is on much safer ground in the earlier part of his paper when he points out that these allotropic changes are equivalent to the production of new elements. If we imagine, for instance, that at a temperature of about 800° C. iron turns into copper we do not need to say to ourselves that the copper has this sudden change of the orbits so that they are going to turn into an unstable position. It appears to me that if this latter were the explanation, then the temperature at which the change takes place could be varied by the strength of the magnetic field in which the whole iron was placed. We know that in the gaseous state—and, after all, most of what we know about electron orbits is when they are in the gaseous state—the electrons revolve in a variety of orbits. We know also that when they change those orbits they do not do it gradually but with a sudden jump from one orbit to another. Whether that happens in the solid state or not I do not know, but it does appear to me that some such change of a very sudden nature is better able to account for this change which takes place comparatively suddenly at a temperature of about 760° C. These questions, as the author points out, will presently be resolved. Such theories are useful as a guide to further experiment. They do not affect the fact that the author has now placed in our hands a complete knowledge of the permanent magnet as an electromagnetic entity.

Mr. E. A. Watson: The author refers throughout the paper to the carbide being in solution in the Alpha iron, although in one paragraph he states that it is the pattern of a solution which counts. I cannot quite agree with him that the carbide is really in solution. It is in a very similar position, and it is rather difficult to say really when the carbide is in solution and when it is not. A very rough and crude analogy would be to consider a vast crowd of people into which a comparatively small number of strangers of another nationality are introduced. In the beginning the crowd has a sort of friendly feeling for the strangers and gathers them into its midst. Each little group of the crowd takes a stranger and makes friends with him. Then, all of a sudden, war is declared and each little group ejects its stranger from it, but it takes some time for the strangers to gather together to form their own little groups. I look upon hardened steel as being a crowd in which the strangers have been ejected from the groups and have not crystallized to form their own group. Although the difference between the author's conception and my own is really a very small one, it has its importance. If the carbides are really in solution, and the hardened steel is heated so as to give a chance for the recrystallization of the carbide molecules, there should surely be a heat emission corresponding to that absorbed when the carbide goes into solution. I have made one or two experiments on these lines, on cobalt steel, and so far have been unable to trace any sign of the heat emission, though I admit the experiments were only rough ones, and the effect, particularly if spread over a wide range of temperature, may have been overlooked. Possibly the author may be able to throw more light on this subject. After all, it is not a very important point and is chiefly a distinction in

words only. We are all agreed that the carbide is in practically molecular subdivision in the steel. Another point on which I must disagree with the author is on the question of chrome steel, which he dismisses rather briefly. In fact he refers to the chromium as helping to retain Gamma iron in hardened steel, and as diminishing the magnetism in the finished magnet. I will grant that chrome steels are not quite as good as tungsten steels, but I do not think that there is very much difference between the two. It is natural that the author, being a master in the art of tungsten steels, possibly might not give credit to the others, but it is certainly significant that chrome steel should be used so largely in other countries. In the United States one hardly ever sees the tungsten steel magnet; all the magnets are of chrome steel, and the figures given to me last summer in the United States by a good many users of chrome steel magnets showed that they were getting energy values very little inferior to those obtained with tungsten steel magnets in this country, and certainly the remanence values were very little less than the figures given by the author. At the same time chrome steels are considerably cheaper than tungsten steels, and I believe it is true that on a basis of cost only the chrome steel magnets show an advantage. Further, the chrome steel magnet is said to give less trouble in hardening than the tungsten steel magnet, although on this point I have no first-hand experience. It is, I think, a significant fact that the Ford Company should employ chrome steel magnets in the flywheel generator fitted to the Ford car. I believe it is true that the choice of materials on this car is invariably made with great care, with a view to the maximum ultimate economy and efficiency. But if the author has not done justice to the chrome steels, I am afraid he must be said to have failed to make a fair statement of the case of the cobalt steels. Unfortunately, he does not give the composition of the cobalt steel (which he quotes in Table 9) as giving a value of 30 300 ergs per cm^3 of steel, but the value of 30 300 is by no means the best that can be obtained. With a 35 per cent alloy, values of $(BH)_{max.} = 1\,000\,000$, or say $e = 40\,000$, are by no means uncommon, and I think that any maker would guarantee 800 000, or $e = 32\,000$, for this steel. The author quotes a price of 7s. 6d. per lb. for this steel. Whilst this price is frequently asked, it is really by no means one that is comparable with the other prices given. If we assume that the basis material cost of the steel, without the cobalt, is 15d. per lb., and the cobalt itself costs 10s. per lb. (the present price in large quantities), we obtain a price of $0{\cdot}65 \times 15 + 0{\cdot}35 \times 120 = 9{\cdot}75 + 42$, or 4s. 3¾d. per lb. I am not, of course, suggesting that the author can buy 35 per cent cobalt steel at this figure, as the steelmaker must allow something on the cobalt which he handles, but I am quite sure that 7s. 6d. is an unduly high figure to take. Further, the 35 per cent steel is not, in general, the most economical composition, i.e. it does not give the maximum value of $(BH)_{max.}$ for a given cost, so that a still better comparison might be made, if necessary. Another point which has apparently been overlooked, is that the cobalt steel magnet, being smaller in dimensions and containing less material, is cheaper to handle and to harden than the more bulky tungsten steel magnets which perform the same function. I quite agree with the author that in the general case, where a given magnetic flux has to be provided, and where no limitations of space are imposed, the cobalt steel magnet is not the most economical way of providing the flux, but I do not agree that there is the disparity he suggests. Perhaps one of the most important and novel points raised in the paper is the decay of potency in the hardened magnet. It is well known to magnet makers that there is a considerable falling off during the first day after hardening. It is also a well-known fact to the ordinary magnet maker that the remanence of the steel rises very considerably during the first day after hardening. The author makes no reference to any increase in the remanence, and again my own experience on cobalt steels is that the increase in remanence during the first day or so balances the decrease in the coercive force, and the result is that the value of $(BH)_{max.}$ remains constant, or even rises. A question that arises in this connection is whether this decay in potency may not depend on the type of molecule which gives the potency to the steel; in other words, will the decay in potency be the same when a comparatively slow-moving molecule is employed as when a very mobile molecule is employed? I am thinking now of a comparison between an air-hardening steel and the ordinary water-hardening steel. The author's figures are for water-hardening steels, and as a matter of interest I have taken some figures on an air-hardening steel. Of course, this ageing effect occupies a series of years, so to get comparable results I boiled a magnet in water and took a comparison of the ageing in boiling water for the air-hardening steel as compared with the ageing given in the paper for the water-hardening steel, and I found that whereas in the author's case the tungsten steel lost about 5½ per cent of its potency in seven hours' boiling, the air-hardening steel lost only 3½ per cent in 48 hours, which seems to indicate that possibly the nature of the potency-giving molecule may have quite an appreciable effect upon the decay in potency. I think I might say that if it were for one clearly proved statement alone the paper deserves a place in posterity, and that is the proof that Beta iron is not the cause of hardness of a properly hardened steel. Many metallurgists, who should know better, have made this statement—let us hope that hereafter it will be made no more.

(*Communicated*): The author's explanation of the spoiling of tungsten steel would appear to be a very reasonable one. In the case of cobalt steels there is little doubt that a similar condition of affairs holds, particularly in view of the tendency of cobalt to promote the separation of graphite, but it would appear possible that there is another cause of the spoiling of steel, and that is in the tendency of the carbides to coalesce during annealing. Certainly spoiling can occur in cobalt steels through annealing at comparatively low temperatures, and this spoiling can be remedied by heating the steel to a comparatively high temperature. The temperature, however, is considerably less than that corresponding to the formation of Delta iron. A temperature of 1 150° C. seems to be quite effective, and

unless in these cobalt steels the Gamma-Delta transformation occurs at a lower temperature than in a carbon steel, the explanation given by the author does not hold. Much more research work is really required, however, before it is safe to dogmatize as to what does, or does not, happen in a steel of this nature. The author's reference to cobalt as a counteracting agent for the effect of chromium in reducing the amount of Alpha iron, strikes me as a little strange. True cobalt does simulate the effect of an increased proportion of Alpha iron, but that is really another story. We have all heard of the cobalt-iron compound corresponding to the formula Fe_2Co, which has a saturation density some 15 per cent greater than that of pure iron, and we should naturally expect that, other things being equal, the substitution of iron by cobalt would raise both saturation density and remanence, or, as the author would put it, would increase the average magnetomotive force of the current rings. This hardly seems to be quite the same as counteracting the influence of chromium. In fact the properties of a series of steels with constant chromium and increasing cobalt furnish no such evidence and show no increase in the apparent proportion of Alpha iron, which could not be accounted for by the presence of Fe_2Co. Right through the paper there appears to run the tacit assumption that in a properly hardened tungsten steel magnet which has not been ultraheated the whole of the iron (apart from that combined with the carbon as Fe_3C) is in the Alpha or magnetizable form. It is a very simple conception and one which makes the structure of a properly hardened magnet extremely simple, but I think that experimental evidence casts a little doubt on this, for if we take the composition of tungsten steel given in Table 11 and, after making allowance for that portion of the iron associated with the carbide as Fe_3C, calculate the theoretical value of the saturation density, we obtain a figure of 18 900 (taking pure Alpha iron as 21 500), a value which I think I am safe in saying is never attained nor even closely approached by a hardened tungsten steel of this composition. In fact, if we use the so-called reluctivity relation to calculate the value of the saturation density from the *BH* curve, we usually obtain a value of between 13 000 and 14 000 only, as the saturation density of the iron associated with the carbide molecules. It would, in fact, appear possible that every permanent magnet contains, in addition to the Alpha iron properly associated with the carbide and forming the magnetic structure, a certain amount both of unassociated Alpha iron and also of iron in the non-magnetic condition. As to whether such a state of affairs is purely accidental and due to defect in treatment or material, or whether it is a natural necessity, I think it is impossible to say at the present juncture.

Sir Herbert Jackson: One welcomes any work which thows light upon the nature of magnetism and which shows what increased uses there are for the phenomena of magnetism. In the course of some investigations into the properties of certain suspension parts of galvanometers it has come to this—that in the desire to know what is giving permanent magnetism to certain parts we should like to find out the condition of the iron. Modern methods of chemistry are very subtle, but we came definitely to a point when it was impossible to throw any further light on the subject by chemical study. After prolonged survey, in dealing with permanent magnetism in these materials, it seemed quite clear—and I need not labour this point—that magnetism had carried us a long way further in determining the possibility of whether iron exists in the form of ferroso ferric oxide or in the form of steel. That, I think I may say with certainty, would be entirely outside anything that could be hoped for from work done on a chemical basis. The actual quantities dealt with were almost so small as to be beyond our powers to deal with, but they were in materials from which they could not be separated without destroying the materials and changing their character.

Mr. J. F. Kayser: I do not agree with many of the metallurgical statements made by the author. In the first place I think that he has not paid sufficient attention to the line of research opened up by Mr. Watson. The author in referring to the microscope practically says that it will not magnify enough—that in order to get any indication of magnetic properties by what one may call visual observation, one must be able to see atoms. I think, however, that that is not the case. The steels or the alloys of which magnets are made consist of a conglomeration of crystals and intermetallic compounds, and the forms of those crystals depend upon the arrangement of the molecules in the lattice structure. By observing the type of crystal and its behaviour we can form a very good indication of what is happening within the molecule itself. I think it would be far better not to go to the ultra-microscope or to X-rays, but to examine the steel under, say, 8 or 10 diameters. A good tungsten magnet steel if observed at a magnification of 8 000 diameters shows very little indeed, but if it is etched to show the macro-structure a very great deal can be learned. The author states that Alpha iron maintains in solution naturally—that is without being heated to a high temperature and then rapidly cooled—approximately 0·24 per cent of carbon. I suggest that the figure should be 0·024. It is quite possible to see the carbon existing in a steel containing 0·1 per cent of carbon in the form of Fe_3C. To pass now to the more magnetic side of the question, let us take the spoiling of steel. In the first place it is most difficult to roll the more expensive varieties of steel without hovering for a very long time in the danger zone, and that is one of the reasons why we must spoil steel. Some of us do know how to recover it, but when we suggest the recovery process electrical engineers are up in arms. It is now three years since I suggested a triple heat treatment for magnet steels, and that treatment has been followed to a very great extent upon cobalt steels. In that treatment the steel is first given high coercive force antecedents by being heated to a temperature somewhat higher than 1 150° C. That produces an ultraheated condition, which must be removed by a low-temperature treatment in the vicinity of 750° C. After those two treatments the normal hardening is carried on. My experience with cast magnets does not quite coincide with that of the author. During the last month I have probably

cast something like half a million magnets, and small magnets confirm absolutely what he says. The remanence is quite high and the coercive force is in fact higher than that of a similar composition of forged material; but with larger magnets which maintain something like 80 000 lines a very great falling off in remanence is noticed.

(*Communicated*): I am afraid that, in his endeavours to air the metallurgical aspect of permanent magnets, the author has based explanations of carefully observed magnetic results upon many erroneous statements to such an extent as to detract very greatly from his theories. Referring to the rate of the passage of solid molecules from solution to crystal, he states that, even when red-hot, the process, in the case of solid steel, is found to occupy several minutes. Such is not the case. At the change point iron carbide (Fe_3C) falls from solution exceeding rapidly—in fact, according to most observers, instantaneously—when once the temperature and rate of fall of temperature are favourable for its separation. Later in the paper the author's use of the word "alloy" is very vague and indefinite. Referring to the nickel-iron series on page 747, he states "and from this it was clear that the metals formed an alloy." It is well known that nickel and iron form an infinite number of alloys with one another. Whilst his explanation of the spoiling effect of soaking fits a few of the theoretical deductions which he has quoted, it nevertheless does not fit in with the facts shown by microscopic analysis, and if he examines a series of spoiled and unspoiled magnet steels I think he will finally agree that soaking brings about a visible association of free carbides into, comparatively speaking, large globules, which do not go into solution when the steel is subsequently hardened at a temperature sufficiently low to retain the greater part of the material in what the author would probably call the non-ultraheated condition. My experiments tend to show that the temperature necessary to restore spoiled tungsten magnet steel is considerably lower than that stated by the author, and I have obtained complete recovery at between 1 150° C. and 1 200° C. This high-temperature recovery process leaves the steel in the ultraheated condition, a fact which the author does not seem to have observed. In order to remove that condition it is necessary to adopt an intermediate treatment before carrying out the final hardening. On behalf of a considerable number of Sheffield steel manufacturers I can assure the author that the manufacture of permanent magnets, and of the steel from which they are made, does not proceed on mediæval lines. Whilst the bulk of the best-quality magnet steel made in this country is manufactured by means of the crucible steel process, a very large tonnage is also manufactured in electric furnaces. Melting large quantities in one furnace often leads, however, to the very defect against which the author levels most of his complaints, i.e. spoiling. This is brought about by the fact that it is extremely difficult to cast large masses of steel into small ingots, and when large ingots are produced they must necessarily be maintained at a temperature within the danger zone for a much longer period than smaller ingots. The figures given in Table 9 are very misleading. A 35 per cent cobalt steel gives a maximum available energy considerably in excess of the figure of 30 300 ergs per cm^3 given by the author, and for the past three years it has been procurable in unlimited quantities at a price of about 70d. per lb., i.e. more than 20 per cent cheaper than the figure given in the paper. It is difficult to discuss the results given under Section (16), "The Gradual Decay of Hardened Steel," in so far as they relate to cobalt steel magnets, as the composition of the cobalt steel is not given and, from the demagnetization loops given in Fig. 23, I venture to suggest that either the cobalt steel referred to was of an unusual composition or was not treated to give the highest possible maximum available energy. During the past six years several hundreds of thousands of magnets have been manufactured under my control, and every one has been tested before leaving the works. Whenever possible, the value of $(BH)_{max.}$ has been determined, whilst, in other cases, the flux on open circuit has been checked. On looking through my figures I find that in every case the maximum available energy increases considerably during the first 24 hours after hardening; the coercive force, it is true, falls off somewhat, but the remanence, on the other hand, frequently increases by 300 to 500 lines per $cm.^2$ I have also a series of round straight-bar magnets, which are kept in the laboratory for the use of unskilled testers who test current products, and some three years ago I was very much troubled by being unable to bring up a large batch of magnets to the figures maintained by the standards, but found that during the first 24 hours after hardening there was a very considerable increase, and that after a few weeks they were well up to the figures given by the original standards. In both this and his previous paper the author has avoided any reference to the serious demagnetization brought about by stroking a permanent magnet with a piece of soft iron. It is interesting to note that whilst after stroking a magnet on one side and in one direction for, say, 20 times a state of equilibrium is brought about, the same magnet can be further reduced by stroking it on another side. Another interesting fact is that the demagnetization due to stroking can be very largely eliminated by having a sufficiently thick layer of paint on the magnet, thus preventing absolute contact between the magnet and the soft iron. I should be very glad to know whether the author has any information in his possession enabling him to give a magneto-mathematical explanation of this phenomenon.

Mr. A. Brookes: I am not in agreement with the author's statement that microscopical examination is of little use. Admittedly, in a hardened magnet steel, the higher the magnetic characteristics the more homogeneous the structure, i.e. the less to be seen, but this of itself may be a useful guide. The value of the microscope is, however, in the examination of the steel *prior* to working up into magnets and heat-treating; that is, in the bar form as received from the suppliers. The microscopical examination in this stage does not appear to have been seriously studied by the author or by other investigators. From my investigations into the question of carbon tungsten steel, which the author's work has confirmed, the great secret lies in the perfection of solution. In my opinion, speaking from the industrial

research standpoint of the user of magnet steel, the study may be restricted to a considerable extent to that of the steel prior to hardening. The best heat treatment, a close estimation of which can be determined from the chemical and metallurgical analyses, is then determined experimentally to give the best magnetic characteristics. Until better light is thrown on to the state in the hardened condition, microscopic investigation may be left to the pure research of the metallurgist. A closer study of the theories of solution should provide a definite clue to magnetic properties. The question of the spoiling of magnet steel during the rolling process is an extremely important one. A spoiled magnet steel can readily be detected in the unhardened condition and the degree of spoiling can be determined to an extent that, knowing the general characteristics of the steel with which one is dealing, the drop in coercive force in the heat-treated condition can be estimated fairly closely from microscopical examination. A really good unspoiled tungsten magnet steel shows a uniform structure resembling a badly formed pearlite. Spoiling causes coalesced white areas to appear, and these do not go into solution completely on heating to the hardening temperature. These areas are easily distinguishable at 800–1 000 magnifications and are, I have presumed, a double carbide of iron and tungsten. Whatever they are, they appear to be the reason for the magnetic spoiling of the steel. It is hardly feasible that they can be free carbon, which the author suggests is the cause of the spoiling of magnet steel. There is no sign of these areas in the unetched condition, and the compound does not appear to lie along the grain boundaries. The author considers that the presence of both carbide of iron and carbide of tungsten increases the potency of the solution. Whilst believing this statement to be correct, the suggestion that the double carbide Fe_3CWC causes this increase in potency is, I think, quite erroneous. In fact, as previously stated, I believe that the formation of the double carbide is the reason of the spoliation of tungsten magnet steel. The white areas previously referred to are the important points in determining to what extent a steel is spoiled. That they contain carbon is shown by the decalescence point, which increases with a badly spoiled steel from a normal 780° C. to say 810° C., these temperatures depending, of course, upon the composition of the steel. In the high-temperature recovery process the white areas are dissolved and do not reappear on cooling, provided that the time of passing through the danger zone is reasonably short, such as would be given by drawing the steel from the furnace and allowing it to cool in the air. Two explanations have been advanced regarding the condition of the carbon and tungsten in magnet steels. That by the author is that they are present as Fe_3C and WC. Dr. Swinden suggested Fe_3C and iron tungstide. In support of his conclusion the author submits the coercive-force carbon-content curve of Fig. 9 that indicates a change in rise at 0·39 per cent C. This corresponds to the calculated percentage of carbon (6 per cent) necessary to combine with the amount of tungsten present. This particular curve is an important feature of the paper and is worthy of close consideration. From the inflexion of the curve between carbon contents 0·39 per cent and 0·7 per cent several important statements are derived later. In my opinion such statements, whether in themselves correct or not, are based on a fallacy. I contend that the inflexion in the curve is not correct, and tests over a number of years on steel from many different suppliers and of varying carbon content with approximately 6 per cent W give results which follow a smooth curve throughout from 0·35 per cent C upwards. A 0·55 per cent C, 6 per cent W magnet steel giving in the hardened condition a coercive force of less than 50 would unquestionably be considered as faulty steel. The figure should be approximately 60 as an average. In assuming that the change in the curve is accounted for by the additional potency due to the Fe_3C which is said to appear at this point, the author automatically suggests that previous to this point all the carbon is present as WC. The question of the carbide formations as derived from Fig. 9 requires much further investigation before such a basis can be accepted as authoritative. Following on the above the attempt to determine the degree of spoiling from the curve (Fig. 9) breaks down. I should certainly regard results in the neighbourhood of the inflexion as being due to spoiled steel or to faulty hardening. The explanation given of the abnormally high quenching temperature is also of interest in this connection. It is said that the *carbides* are all in solution at 790° C., and this is generally admitted to be correct. In any case the decalescence point is not appreciably altered from that of plain carbon steel. Therefore WC must be practically the same in dissolving temperature and effect on decalescence as FeC. The author explains that the necessity for an extra 60 to 70 degs. C. over a decalescence quench is to ensure soaking and hardness throughout. According to his theory all the potency-giving elements are in solution at 790° C., so that no advantage should be gained as regards improving the solution by raising the temperature beyond this point, or say beyond 800° C. It is well known, however, that it is necessary to raise the quenching temperature by 50–60 degs. C. above the decalescence point of the steel. The statement that the undisciplined mind demands this ample margin is, I think, an incorrect diagnosis. A very thin specimen giving little heat capacity, even under careful laboratory heat-treatment conditions, cannot be successfully hardened from 800° C., even with a time of soaking up to 20 minutes, if care be taken that this temperature is not exceeded at any time. Magnet steels are contrasted with tool steels, which are said to be hardened only on the outside edge. With tool steels of similar section to the magnet steels we generally use, they are certainly hard throughout. With large tools a softer core no doubt exists. Assuming that part of the tungsten is present as iron tungstide, I would offer this explanation: At 790° C. the iron carbide goes into solution completely, but the iron tungstide is not properly dissolved until a temperature of approximately 840° C. is reached. In this connection Fig. 33 may lead to confusion, unless it is fully appreciated that such quenching results are only given after the pre-heating treatment to 900° C. stated, or say a temperature above 840° C. There is no connection between the curves of Figs. 9 and 33, and the latter does not substantiate the theory in connection with the former. On the theory previously

mentioned regarding the formation of FeW and its solution at 840° C., Fig. 33 simply shows that such a solution may be maintained to as low as 750° C. The author states on page 744 that the tungsten content in a 0·72 per cent carbon steel may be varied from 5 per cent to 6·5 per cent without causing any material change in coercivity. I should like to confirm this and extend it over a period of carbon content from 0·55 per cent to 0·72. The result of such investigations as carried out several years ago came as a distinct surprise. With reference to the condemnation of chromium as a constituent of a tungsten-carbon magnet steel, it is essential in considering the effect of this element that the steel be in the unspoiled condition. Where the manufacturer has solved the problem of producing unspoiled steel, the benefit obtained is marked. With steels containing up to 0·5 per cent Cr with 0·6 C and 6 per cent tungsten, values of coercive force of 67, coupled with over 10 500 remanence may be obtained. With higher percentages of chromium the steel is gradually transferred into the oil hardening class, that is austensitic structure commences to be produced by water quench, with consequent degradation of magnetic properties. Other advantages are also given by the addition of chromium, which, however, are not dealt with by the author. At the same time the addition of chromium is not advisable in the hands of many steel manufacturers, as it is a trap for the unwary and a case where a little knowledge may be dangerous. I do not agree with the statement on page 770 that "it is unpracticable to forge or even to bend a piece of rolled magnet steel without heating it to a temperature within the danger zone." Magnet steel should never be heated beyond 750° C. or at any rate 800° C. during the forming processes. The question of decay of hardened magnet steel is extremely interesting, and is worthy of study. I made some investigations some time ago in respect to the decay of magnetic properties of hardened magnets when held at various temperatures from 100° C. to 400° C. for some hours. The magnets were remagnetized and ageing tests were carried out on them. Unfortunately the investigations were not completed, but they appeared to show that there was a very distinct difference in the decay between magnets which were carried through the temperature treatment in a magnetized state and those which were not magnetized. This point is being further investigated. As regards cracking when quenching between 800° and 900° C.—the usual range—it might be remarked that spoiled steel is naturally less liable to cracking than unspoiled. This is explained by the fact that all the potency-producing elements do not go into solution at the quenching temperature. The presence of chromium exceeding 0·5 per cent in an unspoiled water-hardened steel is an almost certain source of cracks, particularly with complicated shapes. As an example, a steel of composition 0·7 per cent C., 6 per cent W and 0·56 per cent Cr gave a high percentage of cracks with water hardening, but an interesting steel was one of composition 0·56 per cent C, 6 per cent W, and 0·65 per cent Cr, which according to the composition should have cracked freely, but could not be made to crack even with quenching in water from as high as 920° C. and hammering severely. The reason appeared to be, on investigation, that the presence of a proportionally large quantity of the double carbide reduced the sensitiveness so much that cracking did not occur. The author's experience that supplies of magnet steel are usually more or less spoiled will no doubt meet with general confirmation from many users of the material. It appears probable that makers are generally familiar with spoiling and spoiling conditions, but in fairness to them it should be acknowledged that the problem that confronts them is difficult in practice. The question of unspoiled steel is the most important problem before the magnet steel industry to-day, and is one which will have to be dealt with seriously if the trade is to be maintained. The trouble is principally in inconsistency of supplies; it can be stated practically that the technical requirements are solved, and that it only remains for a better handling of the steel, and more careful supervision in the rolling mills, particularly during the last stages of rolling. Is the author aware that certain suppliers have a rolling method which gives indications of being very different from the high-temperature rolling that appears to be largely practised? In my experience I have met with two classes of steel, amounting to several tons from various sources of supply. One class of steel, as supplied by the majority of magnet steel manufacturers, is usually more or less spoiled and the attendant evils of decarbonization and heavy scale are also evident. The other class usually has a very slight blue scale, no decarbonization, and is very rarely even slightly spoiled. In addition, the sulphur and phosphorus contents, more especially the former, are extremely small in the latter class of steel and are comparable with the highest grades of tool steel in this respect. I would suggest to the magnet steel manufacturers, therefore, that from the indications of hardnesses, magnetic tests and micro-structures that we have carried out on these steels, a serious study of the possibilities of low rolling temperatures with low-sulphur steels might be well repaid, and a more careful supervision of the rolling-mill conditions carried out. It would be more satisfactory to prevent the evils of spoiling than to attempt to cure them by the high-temperature recovery treatment, which is rather impracticable from a user's point of view. The investigations above referred to were carried out at the research laboratories of the British L.M. Ericsson Manufacturing Co., Ltd., Beeston, Nottingham.

Mr. A. Campbell: The author, after many years of patient and skilful investigation, has made a most valuable discovery which throws a flood of light on all the worrying inconsistencies that have so persistently beset all those who have made researches on magnet steel. He has found how good steel can be spoiled, and, better still, he has found how it can be cured. By this splendid achievement he has earned the heartiest thanks and congratulations of all who make or use permanent magnets.

Mr. L. E. Edwards (*communicated*): The comparisons which the author makes between certain cobalt-alloy magnet steels and tungsten magnet steels tend to give to the tungsten steels an undue proportion of merit. For example, from the results shown in Figs. 24 and 25 the conclusion arrived at by the author is that the

present rate of decay in the cobalt steel is $2\frac{1}{2}$ times greater than that in the tungsten steel. Now the *present* rate of decay cannot reasonably be taken to include the decay which took place during the first 12 months after hardening, and if that period is excluded it is found that between the 12th month and the 52nd month the decay rate in the cobalt steel is 0·9 unit per annum, and that in the tungsten steel is 0·75 unit per annum. The percentage potency decay works out at 0·54 per cent per annum for the cobalt steel, and 1·12 per cent per annum for the tungsten steel, showing the cobalt steel in a much more favourable light than the author's figures would suggest. Again, in Section (27) when making comparisons between experimental results obtained by Prof. Honda on cobalt steels and his own experiments on tungsten steels, the author himself states that numerical comparisons are not justified. The percentage reduction in flux density brought about by vibration on a permanent bar magnet does, it is believed, depend partly on the ratio of its length to virtual diameter and partly on the coercivity of the magnet steel. It would be manifestly unfair to compare the effect of shock on two magnets, one having a ratio (length: virtual dia.) of 10 to 1 and the other of 40 to 1. The percentage fall in flux density, assuming both magnets were made from exactly similar steels would be greater in the latter magnet than in the former. Prof. Honda's vibration tests were, it is understood, made on a cylindrical bar magnet 20 cm in length and 0·5 cm in diameter, giving a so-called dimension ratio of 40 to 1. The author would appear to feel that the potency decay taking place must tend gradually to diminish in rate; he is not, however, definite on this point. Judging from the curve given in Fig. 24 there would seem to be reasonable justification for the statement that the potency decay rate is gradually falling. To substantiate such a statement further the curve given in Fig. 34 may be cited as evidence, it being granted that ageing by time and by heat are to all intents identical in their effects on the internal structure of the steel. There is one point which must be well known to the author but which has not been raised, viz. the effect of "stroking" a permanent magnet with any magnetic substance. Taking any ordinary bar magnet in the magnetized condition it is found that vibration has an appreciable but a relatively small effect; whereas if the magnet be stroked with a piece of magnetic material there is an immediate and very large reduction in flux density. In this way, by stroking the whole of the exterior of any permanent magnet a very large reduction in flux density may be caused. It is found that the rate of loss in flux density caused by the stroking of a permanent magnet tends gradually to diminish and seems eventually to reach a point where stroking has no further effect. The author's explanation of the reasons for the demagnetizing effects of stroking would be instructive.

Mr. R. C. Woods (*communicated*): It would have been interesting had the author considered to a greater extent the electronic orbit theory of the magnetic atom instead of providing an ingenious and stimulating conception of the magnetic condition in a strictly limited sense, and to have taken more account of its significance as regards the (at present) non-magnetic substances. Admitting that our range of temperatures is limited, it seems strange, if the theory be true, that so very few substances exhibit magnetic properties in a state of unstable molecular equilibrium and none, so far as can be seen, have the electronic orbits fundamentally oriented in the stable condition. It would appear necessary to seek new methods of attack in order to follow up this line of thought to practical ends. The author states that the accuracy of the magnetic tests was considerably greater than that attained in the analysis of steel. I have considered an accuracy of 1 per cent as attainable for the usual ballistic tests with care and precision, and 2 per cent as excellent for a magnetometer, and if greater accuracy can be obtained by means of the apparatus used by the author a description of the instrument or method adopted would be helpful to those of us who are striving for greater accuracy in magnetic measurement. Judging solely by the difficulties experienced by the author in linking chemical composition accurately with the magnet specimen, it would appear that a short specimen is used, which would tend to render the observed values of coercive force open to much greater inaccuracies than if a longer specimen were employed. Has the author considered the production of the coercive-force carbon-content curve (Fig. 9) with the specimens quenched from a fixed temperature (say 60 degs. C.) above the decalescence point in each case. If the data are available, the production of such a curve would be well worth while, and I suggest that it would be of greater value in giving an indication of the available potency in the steel than the constant figure taken by the author when one considers that the decalescence range is approximately 100 deg. C. In this connection, too, within the commercial range of 6 per cent tungsten steel, the quench to give optimum coercive force should also give the maximum remanence obtainable within the hardening range of an unspoiled steel, thus giving the maximum available energy. Unless a strictly comparative basis be taken for the curve in question, the assumptions founded on that curve are open to doubt, and from my experience I do not consider that such an inflexion as that given in Fig. 9 would be obtained. With regard to the suggestion in Section (16) that softening may have been observed in carpenters' tools preserved over a period of 70 years and upwards, I have one or two tools, whose age is at least 80 years, of which the blades are still quite good, a Brinell test on a rabbet plane blade giving a hardness of 630. This has not, however, been in use for the past 50 years.

Mr. S. Evershed (*in reply*): The discussion, like the paper, has covered a wide field and I must confine my reply to a few of the more salient matters, resisting the temptation to wander in the metallurgical morass. So far as the generation of magnetism is concerned, Mr. Atkinson goes at once to the root of the matter. We were all taught to believe that just as electric current is set going by the electromotive force of a battery, so magnetic flux is generated by the magnetomotive force of an exciting coil. This idea carried with it the corollary that the quantity of flux depended on the reluctance of the flux path, in the same way that strength of current was governed by the resistance of the electric circuit. Just as different substances

differed in their electric conductivity, so different magnetic substances were supposed to differ in magnetic conductivity, or permeability as it was called. To Ampère, with the logical mind of the Frenchman, such a view would have seemed absurd and topsy-turvy. He only knew one kind of space and believed electric current to be the sole cause of magnetism in that space. He explained the great manifestation of magnetism in iron by assuming that every iron molecule embodied a permanent atomic electric current. Such was Ampère's hypothesis and now, a hundred years after his time, the atomic electric current he guessed at has been discovered in the planetary electrons of the atom. It is their powerful magnetomotive force, and not the relatively feeble force of the exciting coil, that creates the enormous flux in a magnetic circuit of iron or steel. To this point the astonishing discoveries of J. J. Thomson, Rutherford and others have brought us and we must adapt our ideas accordingly. What magnetism is, no one knows. We can only think of it as a peculiar condition created in space by the motion of electricity. The moving electricity may be a single electron rushing round its orbit in an atom of hydrogen, or the 26 planetary electrons of the iron atom, or the current generated in a coil by a battery. In every case the result is magnetism, and the space on which the moving electricity acts is the one universal medium. Knowing this, anyone who still finds it helpful to do so may write $B/H = \mu$ to express the numerical ratio of the flux density to the extraneous force arising from the exciting coil. But to regard μ as a physical property, the *permeability* of some particular substance and belonging to that substance in the same way that conductivity belongs to an electric conductor, is to remain blind to the discoveries of the last twenty years.

Turning to the suggestion put forward in Section (11) that pressure may be the controlling factor in the magnetic change, I fully share the difficulty Mr. Atkinson has expressed in forming any rational idea of the mode in which pressure might act on the orbits of the planetary electrons. We all believe pressure to be kinetic in origin, but it has to be remembered that the kinetic theory of pressure was formulated in days when atoms were assumed to be something like diminutive billiard balls. Possibly the classic theory of pressure will have to be recast when the structure of the electronic atom has been settled.

Mr. Watson gives us a happy simile for the state of things in hardened steel. But to complete his picture the crowd of human beings must be supposed to undergo some kind of transformation as fundamental as that of Beta iron into Alpha iron. We must imagine a crowd of Frenchmen changing into Englishmen as the result of a change in the climate. In all essentials Mr. Watson's view is that of the paper, but whether the whole of the energy of solution is released before the solute molecules have moved away from their solution positions is rather a moot point. Mr. Watson's experiment of heating a piece of hardened steel and looking for a possible release of energy, is one of great interest. I can readily understand how difficult it would be to secure the necessary precision (there is always a doubt clinging to a negative result), but the experiment certainly deserves to be repeated under stringent conditions.

Another matter referred to in the course of the discussion was the solubility of carbon in Alpha iron. This must not pass unnoticed, although it does not affect the general argument of the paper. I have made no experiments on solubility, and for facts outside my own observation I have relied on what I could glean from metallurgical textbooks. But on this question of the solubility of carbon in iron I could not find anything definite to go upon. To repeat what is said on pages 739 and 740, information as to solubility is scanty and vague. References are frequent to some unspecified degree of solubility in Alpha iron, but the solubility is implied rather than stated as a matter of observation or measurement. To co-ordinate this vague information with the known coercive force of softened steel, I made the simplest possible assumption; namely, that the solution of the carbide was the only source of potency that need be taken into account. In other words, I assumed that in softened steel any potency arising from carbide in the crystalline state would be very small and might safely be neglected. On this basis it appeared that about 0·26 per cent of carbon would be retained in solution in Alpha iron, a quantity in good agreement with the statements made by more than one metallurgical writer of eminence, as to the carbon content of steels that "could not be hardened."

But Mr. Kayser points out that it is possible to *see* the carbide in the crystalline state when the carbon content of the steel is so small as 0·1 per cent. The same criticism, and on the same ground, has reached me from another metallurgical quarter, and I suppose that what is seen in softened steel of very low carbon content is the crystalline structure known to the metallurgist as pearlite—a visible structure which is formed when the carbide Fe_3C and the Alpha iron undergo crystallization simultaneously. Then again, since the reading of the paper a brief note has appeared in *Nature* from which I gather that Prof. Honda has quite recently determined the quantity of carbon soluble in iron (presumably Alpha iron is meant) and finds it to be 0·035 per cent *). Clearly the metallurgical evidence is against me, and if our mental picture of the state of things in softened steel is to accord with the facts, the potency arising from the crystallized carbide must not be left out of account. That is to say, the coercive force of a piece of *softened* steel must not be attributed solely or even mainly to the pattern of solution, as it is in the paper. It must be thought of as arising from a more complicated pattern constituted partly by crystalline carbide, partly by solution. With this correction, the phrase surplus carbide, when it is used in the paper in connection with magnet steel containing about 0·7 per cent of carbon, must be interpreted as meaning more than nine-tenths of the whole amount of carbon in the steel, whereas throughout the paper the surplus is assumed to be about two-thirds of the carbon content.

* *Nature*, 1925, vol. 115, p. 656. The reference is to the Science Reports of the Tohoku University, vol. 13, No. 2. How the determination was made I do not know. I am writing this reply several hundred miles from the nearest metallurgical library and cannot refer to the original Report.

Another point of theoretical interest may be noticed. By means of a novel method of observation (the experiment is recorded in Fig. 12) I have shown that in a piece of tungsten steel containing 0·65 per cent of carbon, the time occupied by the surplus carbon in passing out of solution as the temperature fell from 708° to 650° C. was 2 minutes, as nearly as the time can be determined. Looking at Fig. 12, it is clear that the passage from solution to crystal must have begun at or a little before the point corresponding with 29 minutes on the time scale, where the energy curve begins to turn upwards. The process cannot have come to an end before the completion of the magnetic change at minute 31, a point which marks the end of the transformation from Beta iron to Alpha iron. Hence the time occupied by the passage from solution to crystal was certainly not less than 2 minutes. I see no escape from this conclusion and cannot accept Mr. Kayser's statement that the transfer process is an all but instantaneous affair. I do not know on what experimental results he founds his belief. I have, at various times, integrated numerous inverse-rate cooling curves, including those of Osmond, of Carpenter and Keeling and others, and in every case the duration of the transfer has proved to be considerably more than 2 minutes, often being as much as 5 minutes or even more. The experiment recorded in Fig. 7 is a case in point, the duration of the passage from solution to crystal being at least 6·5 minutes in this experiment.

Mr. Brookes dismisses the carbon-coercive-force curve for tungsten steel (Fig. 9) as untrustworthy, mainly on the ground that it is not in agreement with a number of coercive-force tests which he has collected from various sources. Mr. Woods is also reluctant to accept the double curve. I have already referred on page 742 to the extraordinary discrepancies in the figures when coercive-force values obtained by different observers are brought together, and it was the difficulty of making any sense of them that led me to investigate. The outcome was as contrary to my *a priori* notions as it is to the opinions of Mr. Brookes and Mr. Woods, but when my critics have had a little more time to study Section (10) and to note the precautions taken to ensure accuracy, I am confident that they will find themselves compelled, as I was, to accept the double curve, given in Fig. 9, as a fact.

Mr. Edwards has fallen into an error in supposing that the figures, given on page 766, for the present rates of decay in tungsten steel and cobalt steel include the decay which occurred during the first year after hardening. My figures for the annual change, namely 0·8 units and 2·0 units respectively, are based on the experimental data from which Fig. 21 and Fig. 22 were prepared, and represent the rates of decay (slope of the decay curves) at the end of the third year, as nearly as they can be determined. As I have pointed out in the paper, the intervention of the seasonal change makes a precise statement impossible for the first two or three years, and it would certainly be rash to base any estimate on a decay curve like that shown in Fig. 24. Several more years must elapse before we can obtain entirely trustworthy figures for the relative rates of decay in the two kinds of steel. In the meantime, I naturally prefer my figures to those of Mr. Edwards, and I believe they are not so very far from the truth. I agree that decay in time and decay by heat must be on all fours as regards the effect on the molecular pattern. In my opinion, decay in time is in fact decay by heat and, if that is so, nothing short of reducing the temperature of the hardened steel to absolute zero would put a stop to decay.

Replying to Mr. Woods, I hope before long to deal with magnetic measurement, especially as applied to magnet steel, and a description of my magnetometer must be deferred until then. I may, however, mention one feature which I believe to be unique:—the instrument contains no magnetic material of any kind whatever, other than the specimen of steel under test. For all work requiring accuracy test-pieces of ellipsoidal form are used, and the applied magnetic field being uniform throughout the length of the test-piece, coercive force is measured with great precision. In practice a number of readings are taken for each determination, and the probable error of the mean value is certainly nearer one part in a thousand than one in a hundred. In short, the error in the coercive-force values given in the paper is much smaller than the error involved in the determination of the carbon content of a small specimen of steel by the combustion process.

The effect of stroking a permanent magnet with a piece of iron has been referred to by Mr. Edwards and also by Mr. Kayser. What the stroking does is to break down the orientation of a superficial layer of the steel. How deep the effect goes I do not know, but there is probably a fairly well-defined limit to the mischief that can be done to a magnet in this way. As to the explanation, we may suppose the piece of iron to act as a magnetic shunt to the portion of magnetized steel which it covers. A local flux path is thereby created in which the iron, becoming magnetized, assists in generating the magnetic flux. Where the flux passes from the magnet to the iron and from the iron to the magnet, at the ends of the piece of iron, it is at right angles to the direction in which the steel is oriented. It would therefore exert a force tending very effectively to break up the orientation of the molecules of iron in the magnet, close to the surface of the steel. By moving the piece of iron to and fro along the magnet every part of the surface of the steel is subjected in turn to this local demagnetizing action, and in the absence of a coil field the superficial layer of steel remains wholly or partially demagnetized. By means of a coat of paint Mr. Kayser has shown that the stroking effect is greatly diminished by a small gap between the iron and the magnet. This is just what the Ampère-Weber-Ewing theory would lead us to expect.

The stroking of a permanent magnet with a bit of iron seems at first sight to be a trivial experiment, but a very little reflection shows how closely it approaches the fundamentals of permanent magnetism. In the course of a long acquaintance with permanent magnets, I have met with quite a number of odd phenomena of the kind, easily overlooked and appar-

rently of little importance. Perhaps their chief significance lies in the fact that they so readily fit into their right places when they are interpreted in the light of the theory just now referred to. I wonder whether it will be possible to explain them when the present-day physicist has succeeded in destroying all the well-tried classical theories, without providing anything to take their place.

I come now to the important question raised in the discussion with regard to the economic status of magnet steels in which chromium is used to impart potency, chromium carbide having a far greater power in that respect than the other potency-giving carbides known to us. Mr. Watson and Mr. Kayser take exception to the comparative figures given in Table 9, on the ground that I have underrrated cobalt magnet steel both by placing too little energy to its credit and by taking an excessive price. Mr. Watson founds his objection to my figures on the magnetic energy guaranteed by the steelmaker and on a hypothetical calculation of the price of cobalt steel as the buyer would like it to be. But I can only speak of cobalt steel as I find it, and the energy value given for it in Table 9 is the highest figure I have so far obtained. It is true that much higher energy values are constantly claimed for cobalt steel, but I have yet to see these claims substantiated by properly authenticated demagnetization curves. Ever since the announcement of Prof. Honda's discovery of cobalt magnet steel, a sporadic shower of samples of this steel has descended on Acton Lane Works, and it has been a matter of keen interest to Mr. Finnis and myself to obtain the best possible result from each sample. When the steelmaker supplying the sample has furnished instructions as regards heat treatment and hardening these have been strictly followed, but up to the present time not a single specimen of cobalt magnet steel received by my firm has fulfilled the claims made for it, both the coercive force and the available energy falling a long way short of the values put forward by the various steelmakers who supplied the samples. For example, one of the best of the samples, when tested 18 hours after the hardening, gave the demagnetization curve reproduced in Fig. 23. In this curve the maximum product of co-ordinates is about 690 000, corresponding with $e = 27\,500$ ergs, a figure lamentably short of what is claimed for good cobalt magnet steel.

It is not for me to explain the great disparity between what is claimed for cobalt magnet steel and its actual performance. It is the business of the seller to substantiate his claims. But I may point out that cobalt steel appears to be peculiarly liable to spoiling in manufacture. Moreover, it would seem that some special heat treatment is needed to effect a complete magnetic cure of the ultraheated condition. But if this is so, the buyer has been left to find out these things for himself, no steelmaker having ever said a word to suggest that he was supplying magnet steel in a spoiled condition, nor given a hint about the magnetic effect of what I have called the ultraheated state. I do not for a moment believe that the steelmaker—honest man—was aware of the mischief he was doing. If he had been, he would surely have set about finding a remedy. He could not be expected to say anything helpful about spoiling and ultraheating so long as he knew nothing about them. But now, in view of the facts disclosed in the paper, he cannot help knowing.

Some of my critics seem doubtful about the composition of the sample of cobalt steel included in Table 9. Analyses were duly made of each of the three samples in the table and, to set any doubt at rest, I give them here in Table 9A. The analysis of

TABLE 9A.

Analyses of the Magnet Steels included in Table 9 (page 771.)

Element	Carbon steel	Tungsten steel	Cobalt steel
Iron ..	98·914	92·408	57·815
Cobalt ..	Nil	Nil	31·615
Carbon ..	0·687	0·725	0·728
Tungsten ..	Nil	6·130	6·435
Chromium ..	Nil	0·094	2·870
Aliens ..	0·399	0·643	0·537
Total ..	100·000	100·000	100·000

the cobalt steel discloses an excess of tungsten, but otherwise there is little to take exception to. Assuming the iron-cobalt alloy to be represented by Fe_2Co, we must multiply the percentage of iron by $58\cdot97/(55\cdot85 \times 2)$, in order to arrive at the correct percentage of cobalt. Doing the sum, it will be found that 57·8 per cent of iron requires 30·5 per cent of cobalt. This compares with 31·6 per cent found by analysis, and disposes of the supposition that any deficiency in magnetic energy arose from a deficiency in the content of cobalt. As stated on page 771, this sample of cobalt steel, when tested in the condition in which it was received from the steelmaker, only gave $e = 23\,800$. There was therefore good reason to suspect that the steel had been badly spoiled in course of manufacture, and in order to obtain a better figure a piece of the rolled bar was "restored" by Mr. Finnis. From magnetometer test-pieces, machined from the central core of the rolled bar after its restoration, we obtained the value $e = 30\,300$ ergs per cubic centimetre. This being the highest value I have observed in cobalt steel it was included in Table 9 as making a strictly fair comparison with the tungsten steel specimen, the latter also giving the best energy value I have so far obtained from tungsten steel. The prices given in the table are not hypothetical figures. They are the actual prices charged by the steelmakers for the particular steels, for quantities of a ton or more. Mr. Kayser and Mr. Watson regard these prices as excessive and I am sure that any buyer would be of their opinion. To-day, as Mr. Kayser points

out, cobalt magnet steel is somewhat less expensive. But so is tungsten steel and, roughly speaking, the relative prices are much about the same. In short, energy for energy, tungsten steel is still a very long way ahead of cobalt steel on the score of cost. Of course, there are various technical advantages to be gained by the use of cobalt steel. These are set forth in the paper on pages 771 and 772, and the figures given in Table 9 show very clearly that we cannot have those advantages without paying for them in a largely increased cost for steel. That the information conveyed by the table is unpalatable I can well believe. But facts are stubborn things, and when they are contrary to our hopes they are peculiarly disagreeable.

The question remains whether the best possible magnetic result has yet been obtained, either from cobalt steel or from chromium steel. In the light of knowledge gained in recent years, I cannot help thinking that very considerable improvement is possible. Hitherto, as I have said, steelmakers do not appear to have been aware of the mischief they were doing. At all events they have one and all been content to make magnet steel without paying any attention to spoiling. But now that spoiled tungsten magnet steel and its restoration have been investigated—incidentally at the sole cost of a firm entirely outside the steel-making industry—it may be hoped that the steel-makers will embark on similar investigations of the spoiling that occurs in cobalt steel and also, as I believe, in chromium steel. The other cause of magnetic deficiency, ultraheating, has yet to be mastered. So far as tungsten magnet steel is concerned I think the Appendix to the paper gives all the information which the magnet maker needs to effect the complete curing of the ultraheated state. But in any steel which, like cobalt magnet steel, contains chromium as a potency-giving agent, the ultraheated condition appears to be far more persistent. So much so, that repeated heatings to, and coolings from, the appropriate curing temperature fail to restore the steel completely to the normal magnetic state.* In short, the curing of ultraheated magnet steels which contain chromium calls for systematic investigation, and I suggest that it is now the turn of the steelmaker to undertake a troublesome task. In my belief, research along the lines followed in the Appendix would be amply rewarded. It would not be surprising if the result were to bring chromium magnet steel up to the economic level of tungsten steel, or even above it, and a corresponding improvement might well be effected in cobalt magnet steel. But it must be borne in mind that magnet steel is not a subject for rough-and-tumble experiments; scientific method and precision are essential, more particularly in the magnetic measurements.

The foregoing paragraph must stand for my answer to the references made in the discussion to steels which contain chromium, including chromium magnet steel. I am acquainted with the flywheel ignition magneto of the Ford car and was interested to learn from Mr. Watson that the many magnets it contains are made of chrome steel. But this piece of evidence does not remove my scepticism any more than Mr. Ford's "Peace Ship" removed the warlike atmosphere of Europe. Only a demagnetization curve will convince me, and magnetic evidence of that kind is wanting. The only magnetic data I have seen relating to chromium magnet steel showed it to be decidedly inferior to tungsten steel on the basis of energy and cost. But that was some years ago, and maybe the American steelmaker has improved chromium steel. If that is so, surely it would be a simple matter to produce a few trustworthy demagnetization curves? They would be more convincing than any number of words. I have not, myself, made any experimental examination of chromium magnet steel. It has been quite enough for one experimenter to make a thorough examination of tungsten magnet steel.

In conclusion, I am heartily in agreement with Mr. Brookes when he says that the question of spoiled steel is the most important problem before the magnet steel industry to-day, and that it will have to be dealt with. The fact that magnet steel is spoiled in the making has too long remained in the dark. The truth was bound to emerge sooner or later, and now the cat has been let out of the bag. A few years ago when I first discovered decomposed magnet steel I had to invent a phrase to describe it, *spoiled steel*. At that time makers of magnet steel—with one notable exception—professed to disbelieve in the existence of spoiled steel. To-day we find steelmakers all willing enough —to talk about it. It is an encouraging sign. The ferment is already at work, and when the buyer begins to reject spoiled magnet steel, the stick will begin to beat the dog and sooner or later the old woman will manage to get the pig over the stile. Let us hope that this event will take place in Sheffield, and without protracted delay. It would be only too easy to wait for unspoiled or restored magnet steel to be introduced into England as the latest improvement made by the foreign steelmaker.

* See, for example, an illuminating experiment by Dr. Edwards, in which a specimen of tungsten-chromium tool steel in the ultraheated state failed to return completely to the normal state (judged by the course of the inverse rate curve) after three heatings to 900° C. How many more heats would have been needed to effect a complete cure in the magnetic sense, it is not possible to say. C. A. EDWARDS: "The Physico-Chemical Properties of Steel," p. 187, Fig. 148.

THE ECONOMIC ASPECT OF THE UTILIZATION OF PERMANENT MAGNETS IN ELECTRICAL APPARATUS.

By E. A. Watson, O.B.E., Associate Member.

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Summary.

The paper first describes the principal types of steels at present available for the production of permanent magnets, and gives magnetic data for typical examples. The cost of these steels is then considered, and figures are given for the actual cost of the material of the steels for which magnetic data have been furnished. Consideration is then given to the other costs involved in working and hardening the steel and housing the finished magnet, and a total figure is obtained which enables a comparison to be made of the various steels under different conditions. It is shown that under certain conditions the use of a cobalt steel will affect an economy over a tungsten or chrome steel, while under other conditions the reverse is the case.

Comparison is then made between the cost of providing a given flux by an electromagnet and also by a permanent magnet, allowance being made for the value of the power consumed in the former case. In order to obtain these data an investigation is made of the most economical winding depth of the electromagnet. The result obtained is applied to two typical cases, and it is shown that in small d.c. machinery considerable saving might be effected by the use of permanent fields, particularly where the cost of fuel is high or where the apparatus runs for long hours, and special applications to certain classes of service are suggested.

Finally, some typical examples are considered of the applications of permanent magnets and particularly of cobalt steel magnets, including magnetos, small d.c. generators, alternators, motor-generators, and certain special applications,

Table of Contents.

1. Introduction.

With the introduction during the last four years of the cobalt magnet steels the problem has arisen, first, as to under what conditions such steels can be economically substituted for the older tungsten and chrome steels, and, secondly, to what extent their use might be considered in electrical machinery in which electromagnets have previously been employed. The problem is in most cases purely one of economics, involving a consideration of the relative cost of obtaining a given magnetic flux with the different materials available; but although theoretically the problem is capable of simple solution the actual choice of material is not so easy, owing to the difficulty of accurately evaluating the incidental costs which are not a direct function of the amount of magnetic material employed. While, therefore, it is hoped in this paper to be able to indicate broadly the lines along which development may take place, it is not the author's intention to attempt to lay down any hard-and-fast lines of demarcation between the fields which are best served by any particular class of material.

2. Steels Available for Permanent Magnets.

At the present time (1924) the following materials are available as marketed products, and are regularly employed for permanent-magnet work :—

(*a*) *Chrome steel*, containing about 2 per cent chromium with 1 per cent of carbon. This steel is largely used in America and on the Continent. Its development received considerable attention during the war in countries where tungsten was not available. It is an oil-hardening steel, fairly simple in heat treatment.

(*b*) *Tungsten steel.*—This steel, which has largely been used in this country for magneto magnets, and also in the better class of magnets for instruments (meters, etc.), contains about $5\frac{1}{2}$ per cent tungsten,

from 0·55 to 0·8 per cent carbon, and occasionally about 1 per cent chromium. It can be made for either water- or oil-hardening. Its heat treatment requires some care owing to the risk of distorting and cracking, especially when high coercive forces are aimed at.

(*c*) *Low- and medium-cobalt steels.*—A large number of steels have been made at different times with cobalt percentages ranging from 6 per cent upwards, but the majority have had only a brief commercial existence, and at present this class is represented by a cobalt-chromium series of steels. These are air-hardening steels, containing about 9 per cent chromium, with 0·8 to 1 per cent carbon. A small amount of other alloys, such as tungsten or molybdenum, is added to help the air-hardening properties, and the cobalt content usually ranges from 9 per cent to 20 per cent.

The heat treatment of these steels is somewhat complicated, but on the other hand does not require such accurate temperature control as do the other steels. It usually consists in a preliminary heating to 1 150° C. in order to break up the complex carbides which are present in the annealed bar, and to ensure thorough solution of the carbides. This is generally followed by a quick annealing at about 750° C. to break up the austenite formed at the previous treatment, and this again is followed by heating to about 1 000° C. and cooling in air. Considerable latitude can be given on the temperatures of the first two treatments, and a tolerance of ± 20 deg. C. can usually be allowed on the latter, but careful control of the cooling rate is necessary. These steels are remarkably free from troubles due to cracking and distortion.

(*d*) *High-cobalt steels (Japanese steel).*—These steels usually contain about 35 per cent cobalt, the percentage corresponding to the alloy Fe_2Co, which gives maximum magnetic properties. A large number of these have been produced employing chromium, tungsten, molybdenum and manganese as alloying agents to enhance the effect of the cobalt, although a plain cobalt-carbon steel with this percentage gives fairly good results. A very common composition contains from 3 to 4 per cent tungsten, 1 to 2 per cent chromium and 0·8 per cent carbon, with small quantities of manganese and 35 per cent to 36 per cent cobalt.

These steels are all oil-hardening with a single treatment only. They give little trouble with distortion or cracking, but accurate temperature control is essential, as a slight elevation of temperature above the absorption point promotes the retention of austenite with a low remanence. The cooling rate is also of importance, and it is hence important to use an oil of the correct viscosity and to control its temperature.

Magnetic properties.—It will be readily realized that it is a somewhat difficult matter to lay down the magnetic values of the various steels. Any given steel will, in general, even with the most careful heat treatment, give results which, taken over a batch of magnets, may vary as much as 10 to 15 per cent above and below the average figure for the batch. The maker of the steel, naturally wishing to take the most sanguine view, will frequently quote a figure nearer to the maximum than to the average, while on the other hand if a guaranteed minimum is required, the figure will, of course, be below the average value.

Representative curves for the different steels are given in Fig. 1, while the figures given in Table 1 are taken as representing the average values of $(BH)_{max.}$, which, after all, is the true criterion of any magnet.

TABLE 1.

Material	$(BH)_{max.}$	Stored energy per cm³ of magnet
		ergs
Chrome-carbon steel	230 000	9 200
Tungsten steel..	260 000	10 400
Cobalt-chrome, 9 per cent Co	500 000	19 900
Cobalt-chrome, 12 per cent Co	580 000	23 000
Cobalt-chrome, 15 per cent Co	650 000	25 900
Cobalt steels, 35 per cent Co	800 000	31 800

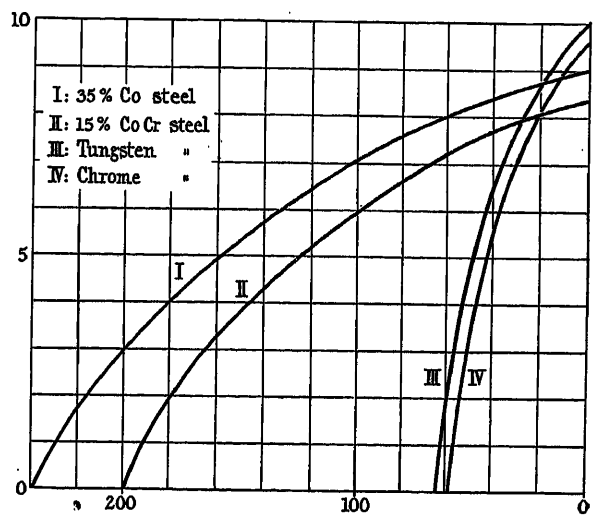


FIG. 1.—Magnetic data for commercial magnet steels.

With the exception of the chrome steels the figures given in Table 1 represent the average values of over 400 000 magnets of which records have been kept during the past few years. They probably represent fairly present-day practice with these steels, but it is, of course, possible that improved results may be obtainable with slight modifications in composition or heat treatment.

Relative costs.—The statement of the cost of a magnet steel is a more difficult problem than the equivalent statement of its magnetic properties, for while the latter is a definite function of its composition and heat treatment, the former depends on many other factors than the composition alone. Even assuming a definite basic price of raw materials, iron alloy, etc., the price of the magnet steel must depend upon other factors, such as the relative difficulty of melting, forging, cogging and finishing, and also upon the amount of scrap produced. Some steels are comparatively easy to work and give sound ingots requiring but little

grinding, and little scrap. Here, again, one must not lose sight of the fact that the ordinary chrome and tungsten steels have been produced in large quantities for many years, and the technique of their manufacture is well understood. Further, competition between steel firms has ensured that their production has been brought down to an economic basis, and that this production is attended with the minimum amount of scrap.

The cobalt steels are at present produced by but few firms. Their production has involved a large amount of experimental work, the costs of which have to be covered, and there is not the same certainty as regards the requisite allowances for waste and scrap. In addition, the price of metallic cobalt is at present a somewhat uncertain factor, as the available sources of supply are few in number and the possible extent of the world's resources is not known with great certainty. Moreover, the refining and distribution of the metal are in the hands of a small number of individuals. During the past three years cobalt has been offered at prices ranging from 10s. to 30s. per lb. Instead, therefore, of actually giving the present quoted prices of cobalt magnet steels, which the author feels can only be regarded as transient, it is proposed to take a basis price equivalent to a tungsten steel, and to add to this the value of the cobalt content estimated at the price of 12s. 6d. per lb. This, it is felt, may be taken as corresponding to a price for the metal of 10s. per lb. plus 25 per cent allowance for scrap, waste and handling charges.

On this basis the prices of the various steels in annealed bar are taken as follows :—

	Pence per lb.
Chrome-carbon steel	6
Tungsten steel	12
9 per cent cobalt steel	25·2
12 per cent cobalt steel	30
15 per cent cobalt steel	34·5
35 per cent cobalt steel	65

3 (*a*). Comparison of Relative Costs of Various Permanent Magnet Steels.

The cost of producing a given flux by means of a permanent magnet is in reality the sum of two quantities, viz. :—

(1) The cost of the magnet itself; and
(2) The cost of housing the magnet.

The former quantity can generally be estimated fairly closely for any given magnet steel, but the latter is a far more difficult problem. It must in any case depend upon the class of apparatus in which the magnet is employed. In certain cases the dimensions of the apparatus as a whole will be determined by the dimensions of the magnet, so that a reduction in magnet dimensions may effect a large saving. In other cases a reduction in magnet dimensions will enable little or no consequential saving to be obtained. For example, in a moving-coil instrument the dimensions of the case are generally determined by the necessity of providing a given size of scale, so that no reduction in overall dimensions could be effected by using a smaller magnet of better material. On the other hand, in an ignition magneto for automobile work, it is the usual practice to make the framework of the machine and cast end-plates conform to the shape of the magnets, so that any reduction in magnet dimensions will bring about a reduction in the amount of gunmetal or aluminium employed, and, by rendering simpler construction possible, may reduce labour costs and charges.

Certain applications arise, of which examples will be given later, where the saving possible by adopting a high-grade steel is out of all proportion to the cost of the steel itself, and in what may be termed the limiting case we have examples where results obtained by such a steel could not under any conditions be obtained in any other way. It is obvious, therefore, that no general expression can be found to take into effect the cost of housing the magnet itself, and the allowance for this must be left in every instance to be determined from an examination of the conditions prevailing in the case in question.

The cost of the magnet may be divided roughly into the following :—

(i) The cost of the steel;
(ii) The labour and charges involved in the necessary work required to bring the magnet to the finished shape and dimensions; and
(iii) The labour and charges involved in hardening the magnet.

(i) *The cost of the steel* has already been dealt with, but it remains to express the material cost given under this heading in terms of the cost per magnetic unit, or per erg of energy stored. In order to save working in very small fractions of a penny, it is proposed to take, as a convenient unit, the quantity 39 800 ergs, corresponding to a value of (flux × M.M.F.) equal to 1 000 000. This would therefore be equivalent to providing a flux of 1 kiloline against an M.M.F. of 1 000, 10 kilolines against an M.M.F. of 100, and so on. Taking this as a basis we obtain Table 2.

Table 2.

Relative Material Cost for Providing 1 *Kiloline of Flux against an M.M.F. of* 1 000.

Material	Volume required	Cost per cm^3	Total cost
	cm^3	d.	d.
Chrome-carbon	4·34	0·105	0·457
Tungsten	3·88	0·211	0·820
Cobalt-chrome (9 per cent)	2·00	0·442	0·884
Cobalt-chrome (12 per cent)	1·73	0·529	0·910
Cobalt-chrome (15 per cent)	1·55	0·608	0·940
Cobalt (35 per cent) ..	1·25	1·14	1·420

From the table it will be seen at once that, given equal conditions in other respects, we cannot expect to obtain

any saving in material costs by employing a better grade of steel.

(ii) *Labour and charges involved in shaping the magnet.*—As in the case of the cost of housing the magnet, it is not possible to obtain any general expression for the cost of bringing the magnet to the desired shape. It is clear, however, that in the majority of cases this will not be the same for a low-grade magnet as for a high-grade one performing the same duty. In most applications it will be found that the low-grade steel has to be bent to a horseshoe or similar shape in order to accommodate the necessary magnetic length, while the high-grade steel can frequently take the form of straight bars, which are merely cut off and hardened. Consequently, much more labour and plant are necessary to deal with the low-grade magnet than with the high-grade one. Further, any bending operation must be done while hot and the bending has frequently to be followed by annealing, introducing fresh charges for fuel, plant upkeep, and depreciation and labour. Even assuming that the high-grade steel undergoes the same operations, the mass of steel to be handled is greater, so that more heat units are involved in its treatment and greater furnace capacity is necessary, while incidental charges, such as transport, are higher for the low-grade steel. Further, if grinding operations are necessary upon the magnet, the area to be ground and the amount of metal which has to be removed are almost certain to be considerably greater in the case of the low-grade material.

All things considered, we shall probably not go far wrong in making the assumption that the labour costs involved are directly proportional to the weight of the magnet. In the case where a bent low-grade magnet compares with a straight high-grade one this assumption will probably favour the former. In the case where both magnets are of the same general shape the high-grade one will be favoured, so that here again our conclusions must be modified in the light of any particular case which is under consideration. In order to embrace different classes of magnets of varying degrees of complication, three different series of labour costs have been chosen, viz. 3d., 6d., and 1s. per lb. of magnet, corresponding to 0·053, 0·106, and 0·212d. per cm^3 of magnetic volume. This, combined with the figures given in Table 2 for the cost of material only gives us Table 3.

It will be noticed from Table 3 that while for magnets of simple shape the low-grade chrome steel still shows to advantage compared with all the others, for more complicated shapes the cobalt-chromium steels show a decided advantage, while under practically all conditions the tungsten steels show up badly as compared with both their lower- and higher-grade rivals. The high-cobalt steel is, however, at a disadvantage under all conditions.

(iii) *Cost of hardening.*—Although the cost of this item lends itself to more exact computation than the foregoing, this also is a quantity which may vary between wide limits. Not only will it depend upon the cost of fuel, whether coke, town gas, producer gas or electricity, but it will also depend—as far as the labour in hardening is concerned—upon the relative intricacy of the magnet. For example, a long, bent magnet of complicated shape will require quenching in special clamps. This operation must be done carefully, one magnet at a time, by a relatively skilled operator. On the other hand, straight magnets of an air-hardening cobalt-chrome steel may be handled by comparatively unskilled labour without the use of any cooling jigs or clamps, and can be withdrawn from the furnace just as quickly as it is possible to pick them up with the tongs. There is no doubt, in fact, that for really large production of magnets of this class a travelling conveyer could be employed, and the human element almost entirely dispensed with. On the other hand the cobalt-chrome steels, as at present employed, require in general a triple heat treatment, so that both the costs of heating and of labour are greater than for steel with a single treatment only.

The author's experience is that the furnace capacity and labour required for treating a steel of this class is approximately double that necessary for the same weight of a single-treatment direct-hardening steel. It is believed that, taking the one extreme with labour, fuel, and overhead charges cut down to their minimum, and with a well-designed plant working at its maximum efficiency, the heat treatment might be carried out at an inclusive figure (labour, fuel and charges) of 2d. per lb. for single-treatment steels and 4d. per lb. for triple-treatment steels. The same figure has been

TABLE 3.

Relative Costs of Material plus Labour and Charges up to Point of Hardening.

Material	Volume	Material cost	Labour + charges at, per lb.			Total at, per lb.		
			3d.	6d.	1s.	3d.	6d.	1s.
	cm^3	d.	d.	d.	d.	d.	d.	d.
Chrome	4·34	0·457	0·231	0·462	0·924	0·688	0·919	1·381
Tungsten	3·88	0·820	0·205	0·410	0·820	1·025	1·230	1·640
Cobalt-chrome (9 per cent)	2·00	0·884	0·106	0·212	0·424	0·990	1·096	1·308
Cobalt-chrome (12 per cent)	1·73	0·910	0·092	0·184	0·368	1·002	1·094	1·278
Cobalt-chrome (15 per cent)	1·55	0·940	0·082	0·164	0·327	1·022	1·104	1·268
Cobalt (35 per cent)	1·25	1·420	0·066	0·132	0·264	1·486	1·552	1·684

assumed for single-treatment chrome and tungsten steels as for high-cobalt steels, it being assumed that the extra labour involved in quenching the chrome or tungsten steel magnet of horseshoe or other complicated shape is balanced by the fact that the cobalt steel must be heated to a higher temperature, viz. 950° C. as against 850° C., and that its heat absorption is greater, necessitating the supply of more heat units to complete the solution of the carbides. With small outputs, less efficient plant and expensive fuel, there is no doubt that the figures given of 2d. and 4d. per lb. might be exceeded and the hardening costs easily run up as high as 6d. and 1s. respectively.

Taking these values and adding them to those of Table 3 we obtain the figures given in Table 4.

Conclusions to be drawn from a study of Table 4.—(1) In no case does the tungsten steel magnet show up to advantage, either as compared with the chrome steel on the one hand, or the cobalt-chrome series on the other, although it does in certain cases compare favourably with the high-cobalt steel.

(2) The chrome steel magnet is the cheapest when the shapes are simple, and the labour and hardening costs are low, but is more expensive than the cobalt-chrome series when the magnets are at all intricate in shape, or when hardening costs are high.

(3) In no case does the 35 per cent cobalt steel show any advantage over the cobalt-chrome series. Except for very special work, where maximum results must be obtained irrespective of cost, the use of this steel does not appear to be economically justifiable.

(4) There is little difference between the various grades of the cobalt-chrome series, except where the hardening and labour costs are excessively heavy. In this case the steel with the highest percentage of cobalt shows a saving in cost.

Effect of cost of housing magnet.—As we have already indicated, it is not possible to obtain a formula which will make allowance for the cost of housing the magnet, and any given case must be worked out on its merits. It is, however, possible to see in a general sort of way to what extent the costs obtained for the magnet itself will require modification, so as to take the cost of housing into account. In meters and measuring instruments we have already seen that it is very problematical whether any reduction in the cost of housing can be obtained, while in magnetos and small generators, in which the magnets are closely embraced by a non-magnetic structure of brass or aluminium, some saving may be looked for.

Leaving on one side any question of saving due to simplification in design, there are probably but few cases in which the saving in structural material, consequent upon a change from chrome steel to cobalt steel (to take an extreme case) would exceed 30 per cent of the weight of the magnet itself estimated as brass, or 20 per cent when estimated as aluminium. This at the usual market prices at present ruling would correspond to an addition of some 4d. to 5d. per lb. to the net material cost of the chrome steel magnet, and would raise all the figures in the top line of Table 4 by approximately 0·3d., while those for the tungsten steel magnet would be raised by a slightly smaller amount. If this allowance be made for the saving in cost of housing, it will be seen that under practically all conditions the cobalt-chrome series compares favourably with the chrome steel and is distinctly economical as compared with tungsten steel, and it would seem that there should be a strong inducement to make use of steels of this series in many of the present applications of permanent magnets, and particularly so in the case of magnetos for internal-combustion engines where a saving in weight or dimensions is always looked on with favour by the user.

On the other hand it must be pointed out that the prices we have assumed for the cobalt steels are lower than those at which these can be obtained at the present time. This discrepancy in price is probably due to the following factors, among others:—

(1) Increased difficulty in working of the high-chromium alloys, which retain their rigidity up to high temperatures and are consequently difficult to forge.

TABLE 4.

Total Works Cost of producing Magnets to give a Value of Flux × M.M.F. = 1 000 000.

Material	Good hardening: Hardening cost	Good hardening: Total cost A	Good hardening: Total cost B	Good hardening: Total cost C	Bad hardening: Hardening cost	Bad hardening: Total cost A	Bad hardening: Total cost B	Bad hardening: Total cost C
	d.	d.	d.	d.	d.	d.	d.	d.
Chrome	0·153	0·841	1·072	1·434	0·459	1·147	1·378	1·840
Tungsten	0·136	1·161	1·366	1·776	0·408	1·433	1·638	2·048
Cobalt-chrome 9 (per cent)	0·141	1·131	1·237	1·449	0·423	1·413	1·519	1·731
Cobalt-chrome (12 per cent)	0·122	1·124	1·216	1·400	0·366	1·368	1·460	1·644
Cobalt-chrome (15 per cent)	0·109	1·131	1·213	1·377	0·327	1·349	1·431	1·595
Cobalt (35 per cent)	0·044	1·530	1·596	1·728	0·132	1·618	1·684	1·816

NOTE.—The headings A, B, C to the columns indicate values of "labour + charges" as given in Table 3 of 3d., 6d., and 1s. per lb. respectively.

(2) Greater loss in metal in grinding and trimming operations.
(3) The natural desire of suppliers to recoup the cost of their original development work within the shortest possible time.
(4) Lack of complete data as to causes of scrap and possible scrap percentage which may occur.
(5) The comparatively small quantities in which the alloys are made at the present time, with the high attendant costs for fuel, labour and overhead charges.
(6) Uncertainty as to stability of prices of metallic cobalt.

As regards items (1) and (2), it is to be hoped that extended experience in manufacture will lead to the discovery of means of overcoming the high attendant costs under these headings, or possibly that research may lead to the discovery of an alloy with easier working properties and yet giving the same magnetic results. Item (3) is merely a temporary factor which will gradually decrease with extended use of the material and increased competition, while item (4) also will doubtless decrease as extended experience in the technique of manufacture becomes available. Item (5) is, of course, dependent upon the other factors and cannot be attacked directly, but reductions under this heading may undoubtedly be looked for, in so far as the use of the steel becomes more extensive. Item (6) is probably one of the most important factors operating, and is the one to which particular attention should be paid. The production of cobalt has in the past been secondary to that of silver, cobalt being a by-product from the silver ores of certain districts of Ontario. Latterly, however, cobalt deposits have been discovered in other parts of the world, notably in Australia, and it would appear that, given the certainty of an extended application of the metal, its development might be increased to a very considerable extent. It is not intended to deal in this paper with the production of the metal nor with the extent of supplies available, as it is felt that the best means of drawing attention to the possibility of the commercial exploitation of these is to define the conditions under which an extended use of the metal would be economically justifiable.

In particular it is desired to point out the disastrous results which would follow an artificial inflation in price such as occurred in 1920–21 when the price of the metal was forced up to 30s. per lb. Such a step would render absolutely hopeless any attempt to use it on a commercial scale as a constituent of magnet steel.

3 (*b*). Comparison with Electromagnet.

The simplest consideration of any ordinary application of an electromagnet will show at once that the M.M.F. per cm length of the wound portion of the magnetic circuit is so much higher than is possible with tungsten or chrome steel that the substitution of such a magnet for the electromagnet could only be made possible by a pronounced alteration in general design. In the case of cobalt steels, however, which can be worked normally at values of H ranging from 120 to 160 or higher, the length of cobalt steel required to replace a wound core is generally of the same order of magnitude, and the substitution can often be made without such drastic structural alterations as would otherwise be necessary. The problem then becomes one which is capable of mathematical treatment, although it is not, of course, possible to obtain any general formula, applicable to any case of an electromagnetic system, which will tell us immediately whether or not a saving can be attained by the substitution of permanent magnets. Every system must, for really accurate results, be examined on its own merits. It is possible, however, from a general consideration to arrive at conclusions which may give some idea as to whether a given problem is worth more detailed investigation or whether the suggested alteration can be immediately dismissed as unlikely to be of economic value.

In comparing the permanent magnet with the electromagnet, we have on the one hand to consider the cost of the steel and of its working and hardening, on the basis already outlined under the first section of this paper. On the other hand we have to take into account the following factors :—

(1) Cost of iron core.
(2) Cost of insulation.
(3) Cost of winding.
(4) The necessary labour and overhead charges on the foregoing three items.
(5) The capitalized value of the energy wasted in the magnetizing coil.
(6) Any accessory apparatus which can be dispensed with when a permanent magnet is employed.

This latter item is not amenable to general calculation, as it depends entirely upon the specific purpose to which the magnet is to be applied. In some special cases this factor may be the predominating one, e.g. in a small alternator the use of a permanent field may save the expense of a separate exciter, while in a dynamo it might enable a field regulator and a certain amount of wiring to be dispensed with. Again, in the case of a motor the direction of rotation of which had to be reversible from a distance, the use of the permanent field would effect a considerable saving of copper in cables, etc.

Let us, however, leave out item (6) as applying to special cases only, and consider only the economic aspect of direct substitution of a piece of permanently magnetized cobalt steel for one of soft iron surrounded by its necessary winding.

Imagine a circular magnet of length 1 cm to supply flux to an external circuit of constant magnetic reluctance. Let a be the radius of the magnet, and b that of the outside of the magnetizing winding, and neglect for the moment the insulation round the core, so that a is also the internal radius of the magnetizing winding. Consider the winding as consisting of one turn per cm only, and let ρ denote the specific resistance after making due allowance for the space factor of the copper and insulation.

Then, considering a section of the magnet 1 cm long, we have :—

Area of cross-section of winding $= b - a$
Mean length of turn $= \pi(b + a)$

$$\text{Resistance} = \pi\rho\frac{b + a}{b - a}$$

If I be the current flowing, watts $= I^2R$

$$= \pi I^2\rho\frac{b + a}{b - a}$$

$$\text{and M.M.F. per cm length of magnet} = \frac{4\pi}{10}I.$$

If the latter quantity be fixed, I also becomes fixed, and we have :—

$$\text{Watts lost per cm} = \text{Constant} \times \frac{b + a}{b - a}$$

This quantity, infinite when $b = a$, tends to a lower limit as b is increased indefinitely, but it never vanishes. Hence, no matter how much winding may be put on, a certain waste of energy is inevitable. The lower limit when b is large is :—

$$\text{Watts per cm length} = \pi I^2\rho.$$

This quantity does not contain the dimensions of the magnet involved, hence in the case of an electromagnet it requires no more energy in the limiting case to provide the magnetizing force in a large magnet than in a small one. So that, as far as energy consumption is considered, the magnetic system is clearly more likely to offer possibilities for the use of cobalt steel when the system is of small dimensions.

The value of $4\pi I/10$ for the electromagnet depends only upon I, the current passing, and is limited in general by conditions of heating, apart from economical considerations.

Determination of value of I necessary to make electromagnets equivalent to permanent magnets.—For the two magnets to be equivalent the values of M.M.F. available outside the magnet must be equal. In the case of a properly designed permanent magnet this is equal to the value of H at the point of $(BH)_{max.}$ multiplied by the length of the magnet. As a basis of comparison let us take the 15 per cent cobalt-chrome steel, the properties of which are given in Table 1. This steel has a $(BH)_{max.}$ of 650 000, occurring approximately at $H = -130$, the corresponding value of B being 5 000. Since a value of H of 130 corresponds to $I = 130/1{\cdot}257 = 104$, we obtain for the minimum value of watts per cm length

$$\pi \times 104^2 \times \rho = 3{\cdot}4\rho \times 10^4$$

The value of ρ will vary from $1{\cdot}67 \times 10^{-6}$ for cold copper, with unity space factor, up to as much as 10^{-5} for fine windings. We may take the usual range as being from $4{\cdot}5 \times 10^{-6}$ for heavy windings to 9×10^{-6} for ordinary d.c.c. wire in fairly small gauges. The watts per cm length then range between 0·15 and 0·30.

This comparison, it should be noted, is favourable to the electromagnet, as it presupposes the whole of the M.M.F. to be available externally. Actually this is not so, as a certain proportion will be necessary to overcome the reluctance of the iron itself. If the flux density is fairly low, say B not greater than 10 000, the error will only be of the order of 10 per cent, increasing the value of the loss by this amount in the case of the electromagnet.

The minimum loss figure is not, however, the value which can be usually taken, as it holds only for a winding of infinite depth. If we take a value of $b = 2a$, which represents the maximum winding depth usually employed, the loss figure will be increased in the ratio of 3 to 1.

The most economical winding depth is a matter which requires considering in the light of the cost of the material and of the power wasted. The volume of copper per cm length is

$$\pi(b + a)(b - a) = \pi(b^2 - a^2)$$

and its value is

$$p_c\pi(b^2 - a^2)$$

where p_c, the cost per cm³ of copper + insulation + labour cost and charges, varies from about 0·125d. for heavy wires to 1·5d. for fine wires of the order of 40 S.W.G.

The energy loss is, as we have seen,

$$\pi I^2\rho\frac{b + a}{b - a}$$

The capitalized value of the energy loss will be

$$\frac{100}{p}nk\pi I^2\rho\frac{b + a}{b - a}$$

where p is the rate of interest allowed on capital cost, $n =$ (number of hours worked per annum $\div$ 1 000) and $k =$ cost of power per kWh.

The total capitalized cost is given by the expression

$$\pi p_c(b^2 - a^2) + \frac{100nk}{p}\pi I^2\rho\frac{b + a}{b - a}$$

We may write this as

$$\text{Capital cost} = \alpha\left[(b^2 - a^2) + \beta\frac{b + a}{b - a}\right]$$

where

$$\alpha = \pi p_c \quad \text{and} \quad \beta = \frac{100nk}{p}\cdot\frac{\pi I^2\rho}{\alpha} = \frac{100nkI^2\rho}{pp_c}$$

Writing b/a as r, the capital cost may be written :—

$$\text{Capital cost} = \alpha\left[a^2(r^2 - 1) + \beta\frac{r + 1}{r - 1}\right]$$

Differentiating with respect to r and equating to zero gives us :—

$$a^2r = \frac{\beta}{(r - 1)^2}; \quad \text{or} \quad r(r - 1)^2 = \frac{\beta}{a^2}$$

and solving this equation by trial for various assumed

values of β/a^2 we obtain the relation between r and β/a^2 which is plotted in Fig. 2.

Using this curve in conjunction with the formula for capital cost, we can write down at once the cost of an electromagnet the equivalent of the 15 per cent cobalt steel, and one which gives the minimum total capital cost for the different values of the various quantities concerned. Owing, however, to the large number of independent variables involved in the cost of the electromagnet, a slightly different method of comparison has been adopted in order to simplify the graphical work involved.

Consider the cost of the cobalt steel magnet itself. We have seen that the density in the magnet is 5 000 at the point of $(BH)_{max.}$, whereas that in the soft iron is 10 000. The section of the cobalt steel must therefore be equal to twice that of the electromagnet, or, as an alternative, we may take it as the same section but reckon the price per cm³ as doubled.

Turning now to Table 4, we see that for a 15 per cent cobalt steel the total cost for a value of $(BH)_{max.}$ area of 1 000 000 varies between 1·131d. and 1·595d. As the shape of the magnet is probably fairly simple we may be justified in adopting a value somewhat below the mean of these two. Let us therefore adopt the figure of 1·25d.

Referring to Table 2 we see that the volume of the magnet is 1·55 cm³, so that the price becomes $1\cdot25/1\cdot55 = 0\cdot807$d. per cm³. Doubling this to allow for the difference in density we obtain :—

Cost of permanent magnet per cm³ = 1·614d.

The actual cost of the cobalt steel magnet per cm length may therefore be written down as

$$1\cdot614\pi a^2$$

while that of the electromagnet is, as we have seen,

$$\pi p_c\left[a^2(r^2 - 1) + \beta\frac{r+1}{r-1}\right]$$

These are equal when

$$1\cdot614\pi a^2 = \pi p_c\left[a^2(r^2 - 1) + \beta\frac{r+1}{r-1}\right]$$

or when

$$\frac{1\cdot614}{p_c} = r^2 - 1 + \frac{\beta}{a^2}\cdot\frac{r+1}{r-1}$$

In order to avoid drawing a series of curves for different values of β, the right-hand side of the equation has been evaluated and plotted in Fig. 3 against the corresponding value of $a/\sqrt{\beta}$. The points of intersection of this curve with the horizontal lines corresponding to the value of $1\cdot614/p_c$ give the transition points. For values of $a/\sqrt{\beta}$ less than these the cobalt steel magnet is the cheaper, while for values greater than these the electromagnet has the advantage. Since the term a occurs in the form of the fraction $a/\sqrt{\beta}$ we see at once that the area of the core at which a change-over is justified varies directly as β. The flux therefore varies directly as β also.

Clearly then the following features all tend to favour the case of the permanent magnet :—

(1) High cost of copper.
(2) Small size of core, i.e. small working flux.
(3) High value of β, which in turn may be due to :—
  (a) Long working hours (high value of n).
  (b) High cost of power (high value of k).
  (c) Bad space factor (high value of ρ).
  (d) Low rate of interest on capital (low value of p).

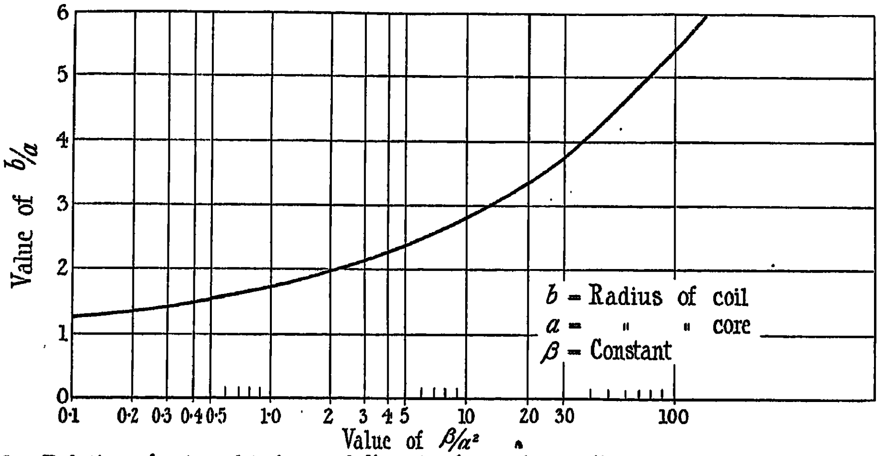


FIG. 2.—Relation of external to internal diameter for various coils of the economical dimensions.

The fact that p_c occurs in the denominator of the quantity β will to some extent balance its effect under (1) above, but as we are concerned with the quantity $\sqrt{\beta}$ its effect will thus be only of secondary importance. The appearance of p_c in the β term is, of course, due to the adjustment which has been made in order to give minimum cost for any given set of conditions, and while this adjustment makes the increase in cost due to rise in value of p_c the least possible, it can never completely offset it.

Examples.—In order to make clear the application of the foregoing formula let us now apply the results obtained to some actual cases, and endeavour to see where the transition points occur in practice.

(1) Let us take first the case of a small, fairly high-voltage, fan motor, or high-voltage generator running for long periods, say 7 000 hours per annum, and using power at a relatively high price of, say, 8d. per unit.

Let us take the copper space factor of the field coil as 25 per cent, giving $\rho = 7 \times 10^{-6}$ approximately.

Take p as 5 per cent, and take the price of copper

+ insulation + charges on winding as 10s. per lb.; $p_c \doteq 0\cdot6$.

This gives us for β the value

$$\frac{100 \times 7 \times 8 \times 104^2 \times 7 \times 10^{-6}}{5 \times 0\cdot6} = 140$$

Fig. 3 shows that the corresponding transition point corresponds to a value of $a/\sqrt{\beta} = 1\cdot8$. Consequently $a = 1\cdot8 \times \sqrt{140} \doteq 21\cdot3$ cm and the corresponding flux would at $B = 10\,000$ be equal to 14 megalines. This is quite a large amount of flux, much larger in fact than corresponds to the small fan motor which we assumed for this example, and would seem to show that for special conditions such as have been chosen, with high energy cost and long working hours, permanent fields might with advantage be employed on quite large machines.

(2) As an opposite extreme let us consider the case

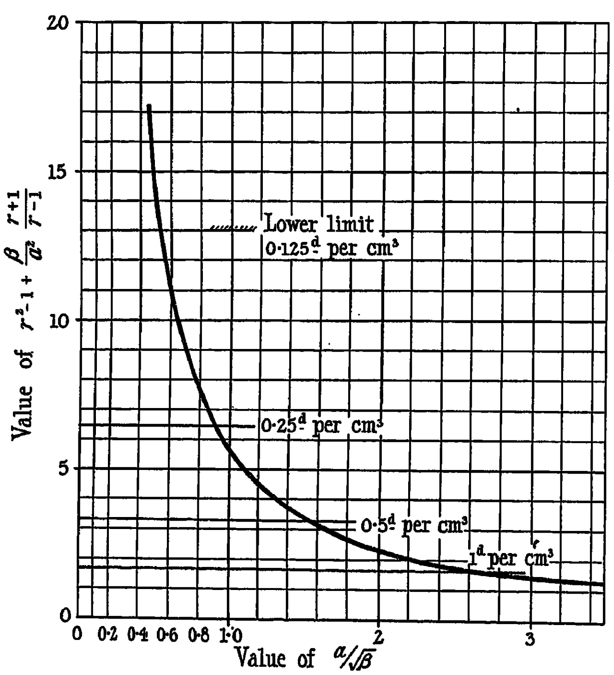


FIG 3.—Determination of transition points where the costs of a permanent magnet and of an electromagnet are equal.

of a piece of apparatus for a fairly low voltage and wound with relatively thick wire. Assume also that the number of hours worked per annum is less, say 2 000, and that power is available at the low rate of 1d. per unit. Take the copper space factor as 40 per cent, and the cost of winding at 1s. 6d. per lb. Then

$$\rho = 4\cdot25 \times 10^{-6} \quad \text{and} \quad p_c = 0\cdot135\text{d. per cm}^3$$

Taking p as before at 5 per cent we obtain:—

$$\beta = \frac{100 \times 2 \times 104^2 \times 4\cdot25 \times 10^{-6}}{5 \times 0\cdot135} = 13\cdot6$$

The point of intersection of the curves on Fig. 2 gives $a/\sqrt{\beta} = 0\cdot59$, so that $a = 2\cdot17$ cm and the corresponding flux at $B = 10\,000$ will be 148 kilolines. Even this amount of flux is considerably more than the working flux of the average small fan, or industrial motor, so that it would seem that under practically all conditions the use of permanent fields for such machines is economically justifiable.

The two foregoing examples will serve to show that even in ordinary small engineering work the use of permanent fields in place of wound ones deserves serious consideration on economic grounds alone, although it will be granted that if first cost alone is to be considered and no allowance made for the capitalized value of the lost energy it is but rarely that the permanent field will show to advantage.

A little consideration will show, too, that in many cases the conditions are much more favourable to the permanent field than in the examples we have chosen. Particularly is this the case where the energy is supplied from primary batteries or small accumulators which only show a low overall efficiency. Examples of these would be portable motor-generators, etc., for wireless work, signalling apparatus, etc., while it would seem that for small petrol generating sets the use of a permanent-field generator might be economically sound. With such a set the fuel cost may easily run as high as 3d. or 4d. per unit, and when to this is added the cost of lubricating oil, etc., it can easily be seen that the transition point will correspond to a generator of some considerable size and that, particularly in the class of a lighting set which runs for long periods and is used with a floating battery of small capacity, the permanent-field machine is worthy of serious consideration. Moreover, the permanent-field machine has the important advantage that its characteristics do not alter as the field winding heats up, so that it is a comparatively simple matter to arrange for the governor to give a constant voltage under all conditions.

4. EXAMPLES OF APPLICATIONS OF COBALT STEEL.

The following examples have been chosen among a number which are available as typical cases of applications which have now been worked out on a commercial scale.

Magnetos.—Cobalt steel magnets as applied to magnetos fall under two headings:—

(i) Applications made without important change of design and on economic grounds only.

(ii) Applications involving radical alterations in design or making designs possible which could not successfully be carried out any other way.

(i) An example of the first of these is given in Fig. 4, which gives sectional views of three magnetos of the same performance, the one employing tungsten steel magnets, and the other two cobalt steel magnets. The actual data for the machines are given in Table 5.

A considerable saving in cost was obtained at the time the change-over was made, but at the present time, owing to the fact that labour costs have dropped more than steel prices, the magnet prices themselves

are slightly higher for the cobalt steel machine. This is, however, offset by the saving in other directions which the simpler and more symmetrical design makes possible, although the difference is only small and would not at the present time justify any firm in changing over from tungsten to cobalt steel.

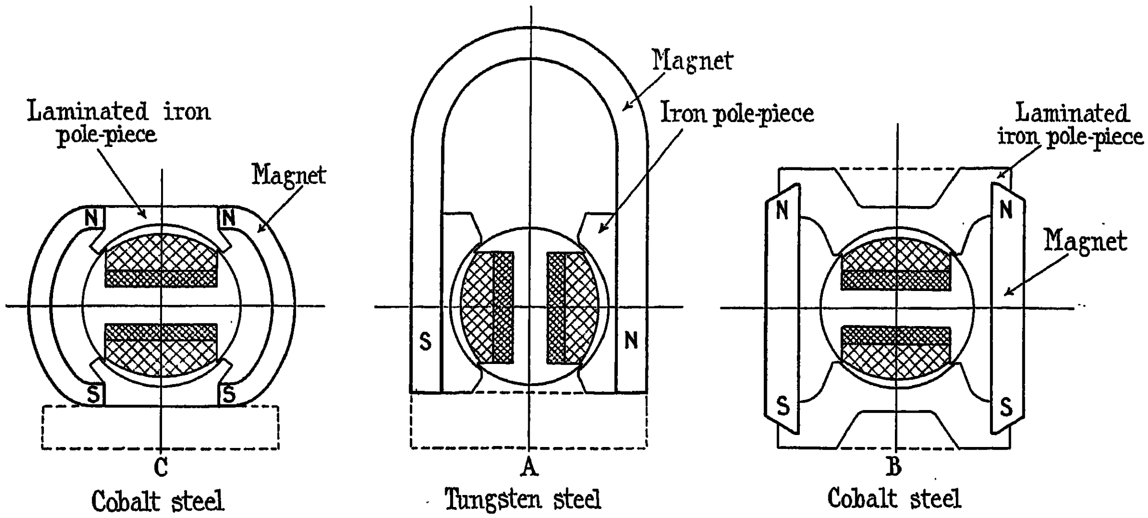


FIG. 4.—Sections of alternative designs of magnetos with tungsten and cobalt steel magnets.

The ordinary magneto, in fact, offers a very good example of a case where a reduction in the price of cobalt steel by about 25 per cent would open up a greatly extended field of use.

TABLE 5.

	Machine C (cobalt steel)	Machine A (tungsten steel)	Machine B (cobalt steel)
Magnet section	$2 \times 55 \times 7 = 7 \cdot 7$ cm^2	70×10 mm $= 7$ cm^2	$2 \times 35 \times 11 = 7 \cdot 7$ cm^2
Magnet length	$7 \cdot 8$ cm	24 cm	$7 \cdot 5$ cm
Magnet volume ..	$60 \cdot 0$ cm^3	167 cm^3	$58 \cdot 0$ cm^3
Material of magnet ..	15 per cent cobalt steel	Tungsten steel	15 per cent cobalt steel
$(BH)_{max.}$	650 000	240 000	650 000
$(BH)_{max.} \times$ volume ..	39×10^6	40×10^6	38×10^6
H at $(BH)_{max.}$ point ..	125	40	125
Available M.M.F. ..	970	1 040	940
B at $(BH)_{max.}$ point ..	5 200	6 000	5 200
Flux at $(BH)_{max.}$ point..	40 kilolines	42 kilolines	40 kilolines

(ii) Under the second category come a number of novel types of magneto, generally of the revolving-magnet type, which have been developed since the advent of cobalt steel. The revolving-magnet type of machine has undoubtedly certain great advantages, particularly as regards mechanical robustness and for aeroplane work, or in cases where the drive is harsh and irregular. A revolving magnet of tungsten steel is, however, very heavy and difficult to accommodate, and its large moment of inertia introduces severe stresses in the shaft and driving gear. The practical development of this type of machine has therefore been rendered possible by the introduction of cobalt steel, although here again the high cost of the material is against the commercial development of this type of magneto for ordinary service.

Fig. 5 gives a sectional drawing of a machine of the revolving-magnet type, designed to give the same electrical performance as the machines illustrated in Fig. 4. Owing, however, to the limitations of space imposed on the magnet, a 35 per cent cobalt steel was adopted, the data of the magnet being as follows :—

Total section	7 cm^2
Length	6 cm
$(BH)_{max.}$	900 000
$(BH)_{max.} \times$ volume	$37 \cdot 8 \times 10^6$
Available flux at $(BH)_{max.}$ point	$39 \cdot 5$ kilolines
Available M.M.F.	960

The adoption of the figure of 900 000 for $(BH)_{max.}$ against the figure of 800 000 quoted in the paper

requires some explanation. It has been adopted for two reasons:—

(1) The magnets are comparatively small in section and it is found that small sections usually give higher figures than larger ones.

(2) These magnets are subjected to a triple heat treatment similar to that already described, which has the effect of slightly increasing the value of $(BH)_{max.}$ even of a 35 per cent steel. Such treatment, while not possibly economically justifiable in the ordinary case, is of value when it is important to get the magnet into the least possible compass.

Small generators.—Generators employing permanent magnets have for a long time been employed for such classes of services as bell-ringing, shot-firing, insulation-testing sets, etc., but not as a rule for the steady generation of any considerable amount of power. Since the introduction of cobalt steel several firms have successfully produced small permanent-magnet direct-current generators for car- and cycle-lighting work. A reduction in cost of material would doubtless result in a very extended application to this class of work.

Further useful extensions of these small machines which may be expected in the future are to small electric lighting sets on the one hand, and to generators for tachometers on the other. A particular instance of the lighting generator which might repay careful study would be in connection with wind motors for battery charging on farms, in country houses, etc. Such a generator, having no field losses, could be made to commence to charge at a very low wind speed, and the average efficiency over periods of varying wind strength would be much higher than for the machine with a wound field.

Used as a tachometer the small generator with cobalt steel magnets would possess many advantages, as, owing to its compactness, it can be very easily housed and could in most cases be driven direct by the shaft whose speed it is required to measure, while

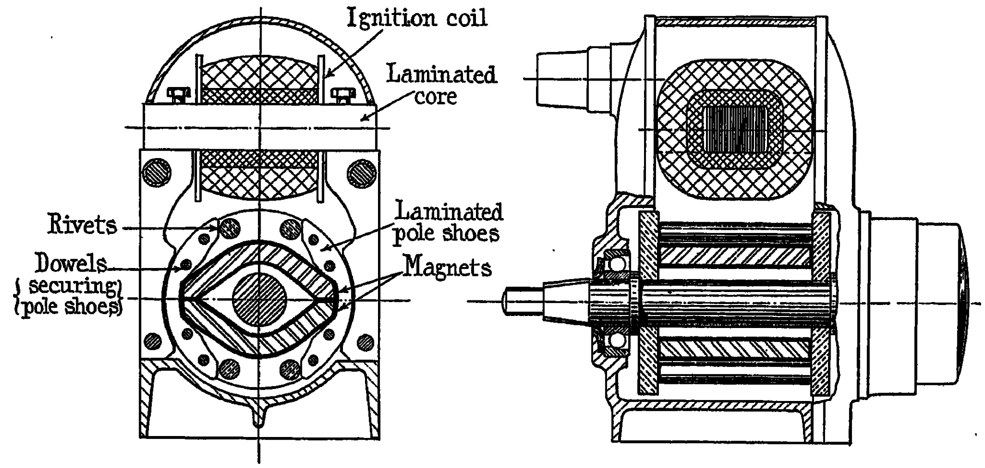


FIG. 5.—Revolving-magnet machine (cobalt steel) designed for same performance as machine illustrated in Fig. 4.

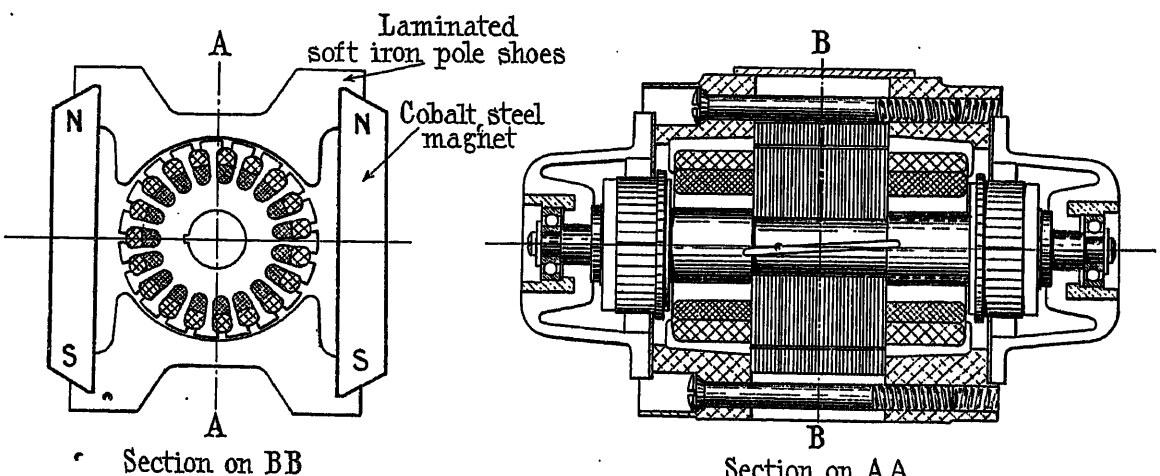


FIG. 6.—Sectional views of small motor-generator with permanent fields. Working flux = 45 kilolines (approx.).

it might clearly form a useful and reliable speed indicator on locomotives of all descriptions.

Motor-generators.—A particular example where permanent fields can be used to advantage is for small

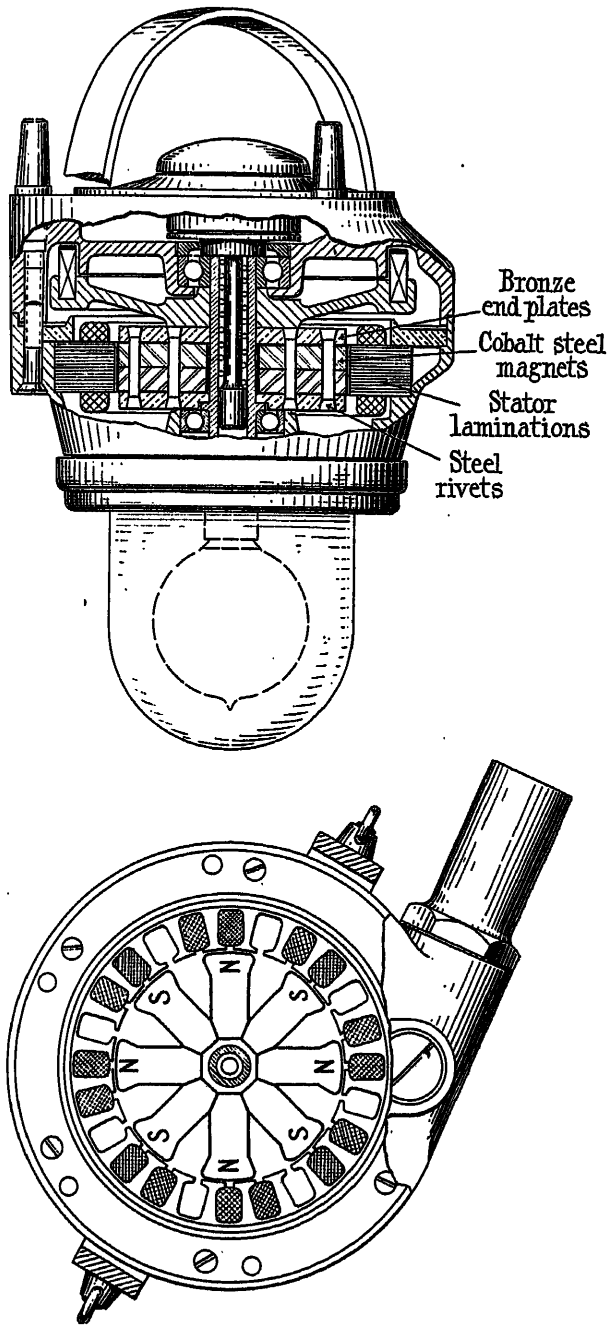


FIG. 7.—Section of air-driven miner's lamp, showing multipolar magnet of cobalt steel.

motor-generators, particularly for wireless work. A number of such machines have been made for supplying the anode voltage for small transmitting sets, receivers and amplifiers. These machines take current at 6 or 12 volts from an ordinary automobile battery, which serves also to provide the filament-heating current, and deliver any required voltage up to 500 on the secondary side. Owing to the use of a permanent field they are light and compact, and the power consumption is remarkably small. For example, a machine giving 120 volts for power-amplifier work takes only 6 watts on the primary side when running light, and of this at least half is accounted for by brush friction. Such a machine has many advantages over the small high-tension battery normally employed, particularly when the voltage and current consumptions are high or where it is to be employed in hot climates. A sectional drawing of such a machine is given in Fig. 6.

Alternators.—While the demand for small alternators in ordinary engineering work is not great, there are certain uses to which such machines are put, and in many cases the cobalt steel magnet will be of very great assistance, particularly where direct current is not available for excitation. Small alternators have been employed for wireless transmission, but at the present time, now that valve transmitters are practically universal, this type of machine is not of importance. They have also been employed on aeroplanes for supplying three-phase current to gyroscopes, and in this case the use of cobalt steel magnets has been found of great assistance in producing a light and compact design. Another special application which may be mentioned is an air-driven miner's lamp, in which the use of a revolving magnet of cobalt steel, driven by a small air turbine, enables a powerful light to be obtained with complete safety from any risk of explosion, even under the worst conditions. Fig. 7 gives a sectional drawing of one of these lamps, and illustrates clearly the mechanically strong and compact construction of the rotor. This construction would be quite impossible were it not for the high coercive force of cobalt steel, which enables the length of the magnets to be kept down to the minimum.

Special apparatus.—There are many applications of cobalt steel magnets apart from the various forms of generators which have just been described, and it is not, of course, possible to enumerate them all. One particular application to which the material has been successfully employed is for polarized cut-outs serving to interrupt the charging circuit of a battery should the dynamo stop or reverse, and there are, of course, many types of polarized relay in which the material might be utilized. Compass needles, again, afford a wide field for the use of steel of magnetic properties superior to those of tungsten or chrome steels. The cost of the material itself is but small, while the gain in pointing power for a magnet of given dimensions and inertia is very considerable.

CONCLUSIONS.

(1) The economy of substitution of a cobalt steel permanent magnet for one of chrome or tungsten steel is dependent upon many factors, and any case requires careful examination on its merits. Generally speaking, the substitution is justifiable where the shape of the magnet is complicated, and where much work must be put upon it, also in those cases where the configuration

of the magnet determines the shape of the apparatus itself, or where extreme compactness or light weight is desired.

(2) The most economical percentage of cobalt would appear to be about 15 per cent, but will depend upon the circumstances involved, the percentage being higher the greater the incidental saving which can be effected by the substitution. The 35 per cent series, while giving optimum magnetic results, is not as a rule economically justifiable at the present price of cobalt.

(3) The price of cobalt is the dominant factor in the situation. A stable price of less than 10s. per lb. would give it a wide sphere of application, while one of 5s. or 6s. per lb. would undoubtedly lead to the complete supercession of chrome and tungsten steels by those of the cobalt series. No widespread adoption can be expected unless there is a reasonable guarantee against exploitation of the supply of metallic cobalt, and reasonable prospect of the price not rising—at all events for some considerable period.

(4) Given the foregoing (stability of price) it would appear that in many instances electromagnets might be advantageously substituted by cobalt steel ones, and that the material might be successfully employed in small generators and d.c. motors up to, at all events, something of the order of 1 or 2 kW rating. This substitution would not in general, however, give a gain in first cost, but only a reduction in losses, which would ultimately repay the extra outlay (if any).

(5) There are a number of special developments which are rendered possible by the properties of cobalt steel and which may lead to its use on a considerable scale, but such developments must of necessity be somewhat slow.

Discussion before the Scottish Centre, at Glasgow, 7 April, 1925.

Prof. G. W. O. Howe: It is somewhat paradoxical that the permanent magnet, which was the first piece of magnetic apparatus ever known, is the piece of magnetic apparatus about which least is known, and the most difficult to design. The average student who could calculate an electromagnet without any difficulty would be quite nonplussed if asked to design a permanent magnet. Another striking fact is that the most common material of construction, viz. iron and steel, is a most complicated material, about which less is known than about almost any other material, and I am sure that everybody will be struck with the complication of the heat treatment described in the paper. One reads on page 823 that the steel is to be preliminarily heated to 1 150° C. in order to break up the complex carbides which are present in the annealed bar, and to ensure thorough solution of the carbides. This is generally followed by a quick annealing at about 750° C. to break up the austenite formed during the previous treatment: the steel is then heated up to 1 000° C. and cooled in air. The metallurgy of steel is truly a very complex business. The importance of permanent magnets is now fully realized. Another thing that must strike anyone reading the paper is the thorough way in which the author has gone not only into the scientific aspect but also into the economic aspect. He is certainly to be congratulated on the very judicial way in which he has inquired into all the pros and cons; he has not unduly boosted the use of cobalt steel but has pointed out both its advantages and its disadvantages. I should like to ask him whether he has had any experience of the permanence of these magnets. It is a very important matter, especially when suggesting the replacement of electromagnets in small motors, to know whether these cobalt steel magnets maintain their magnetism under all conditions.

Mr. A. Brookes: In connection with the question of the use of cobalt-chrome steel for permanent magnets, the problem, in a nutshell, resolves itself into a comparison of the prices of the various available steels. There are really three aspects to the question: (1) The quality of the steel desired; (2) the design of the apparatus involved; and (3) the comparative costs of the various conditions. In regard to (1), I think it might be taken in general that for the majority of electrical apparatus using permanent magnets, chrome steel, although the cheapest, is not of sufficiently high quality for practical requirements, whereas tungsten steel is quite satisfactory except for special cases. In the latter, which are few in comparison, the use of cobalt-chrome steel may be advisable independently of any other considerations; and also in some cases, such as wireless headgear receivers, the question of weight may force manufacturers to use the cobalt steel magnet, even though from other considerations it may not be economical. In regard to (2), in some cases considerable economy might be effected, both in money and in space, by designing the apparatus round the shorter and probably straight cobalt-chrome magnet. In fact, it can almost be stated that, unless this is possible, there is no advantage whatever to be gained by changing from tungsten steel to cobalt-chrome steel except for the special cases cited above. Restricting the problem to the telephone industry, with which I am particularly interested, there is not a single piece of apparatus involving permanent magnets in which, in my opinion, it would be advisable to change over the existing designs involving tungsten magnets so as to bring in cobalt-chrome magnets, with the exception of the headgear receiver referred to above. This statement is only made after very careful investigation into the matter in all its various aspects, and it is an important one from the steel-makers' point of view because the telephone manufacturers are probably the heaviest buyers of magnet steel in the kingdom. In regard to (3), to expand the use of cobalt-chrome magnet steel the cost of such steel in bar form must be appreciably reduced, and unless this be done the further applications of cobalt chrome will, to an appreciable extent, become stagnant. Cobalt-chrome steel has undoubtedly wonderful properties from a technical point of view,

but in practice it largely resolves itself into the higher coercive-force value, which enables the length of the magnet to be reduced to, say, one-third, but does not allow of any reduction in cross-sectional area. In fact, to give the same flux, this should be increased approximately in the ratio of 5 to 4 with a magnetic circuit of small demagnetizing forces. If it be presumed that for most electrical apparatus the tungsten steel permanent magnet (of correct dimensions) gives quite good practical results from a non-ageing standpoint, then the reduced volume is the determining feature as regards (2) and (3). I have had in mind for some time the design of apparatus utilizing revolving cobalt-chrome magnets and pivoted magnets under vibratory stresses, because a useful line is opened here. In many such cases the use of tungsten magnets, under the heavy demagnetizing or vibratory effects, might not give what would be considered to be a practical non-ageing condition. The excessive cost of the 35 per cent cobalt steel compared with that of the 15 per cent steel is to be deplored because of the simpler hardening treatment involved. Possibly further research on the lower-alloy steel will enable the hardening treatment to be simplified. Statistics when dealing with costs involving general conditions can be made to prove almost any desired point, but unless the author can buy to much greater advantage than the quotations I have had from various steel manufacturers, I am inclined to think that the costs quoted in the paper for cobalt-chrome steel are considerably lower than would actually be given in practice, sufficiently so as to upset the conclusions based upon them. I can hardly agree with the statement that "under practically all conditions the tungsten steels show up badly as compared with both their lower- and higher-grade rivals," excepting from the tables quoted. The costs stated for tungsten steels are, in general works practice, appreciably less than those quoted by the author, and, in my opinion, the statement should read as a general conclusion as follows: "Under practically all conditions the low-grade chrome steel is not of sufficiently good quality, whilst the tungsten steel shows up appreciably to advantage over the cobalt-chrome steel unless the design of the apparatus can be sufficiently simplified by the adoption of the latter, or other special circumstances come into play."

Mr. C. H. Wright: Makers of electrical apparatus will welcome the paper, since many cases arise where the ability to use a magnet of the requisite $(BH)_{max.}$ which will go into a small space solves difficulties of construction and opens up a number of possibilities hitherto out of the question. Some 15 years ago I was interested by a suggestion made by a colleague, Mr. E. S. Shoults, to replace the field magnets in a line of fan motors by permanent magnets. The idea was to eliminate troubles with fine-wire field windings in very humid climates and at sea. I went into the question of the size and weight of the permanent magnet and was disappointed. With the new steels the question is quite a different one and distinctly worth consideration. Most of us have had to deal with troubles due to corrosion and humidity effects on fine-wire field windings which often show up on board ship and in humid climates, particularly if the impregnation of these fine windings is not perfect. Such troubles are irritating and sometimes involve a disproportionate expense. What does not exist will not give trouble, and it may prove well in many cases to replace fine-wire wound field-magnets by permanent magnets. I am interested in the making of permanent magnets, my own experience being, however, limited to tungsten steel magnets for electrical measuring instruments. Some 20 years ago the firm with which I was associated decided to make its own instrument magnets, and owing to indifferent results with gas and similar furnaces we built an electrically heated salt-bath furnace, using the molten salt as the resister. The even heating of the magnets in this liquid bath, and the ease of temperature control, had remarkable effects in producing a uniform product and reduced to an extremely small percentage the wastage due to distortion and cracking. Moreover, a batch of magnets could be dealt with much more expeditiously by the salt bath. This bath, I believe, is still in use for the same purpose, and I should be interested to know if the author finds it useful in dealing with the new steels. The possibility of using straight bars with the cobalt steel is very attractive from both the magnet maker's and the constructor's point of view. Quenching with clamps is, in general, awkward. The magnetic stiffness of cobalt steel renders possible constructions of magnetic circuits which are surprising to those accustomed to tungsten steels. For instance, I have used for some three years a little hand-lamp containing a small generator driven by a trigger handle the steel field-magnets of which are only 1 in. long in the flux direction. It is still in use and the magnets do not appear to have weakened at all.

Dr. S. Parker Smith: I should like to have some more information on the substitution of electromagnets by permanent magnets, especially as regards efficiency. When I first had to design motors for desk fans I was astonished to find what a great loss takes place in the field. Only one who has measured or calculated the losses in the exciting circuits of small machines has any idea of their extent. Therefore I think that from that point of view alone it is worth while considering the permanent magnet. At the time I was doing this —some 14 or 15 years ago—I found that it was quite out of the question to use a permanent steel magnet in motors for desk fans and other small loads. Can the author say what is the magnitude of the losses on the pole faces of these hard steel magnets? On the one hand we get rid of the losses in the field coils, but on the other hand it is quite possible that we may get losses in the faces of the poles. With regard to the author's figures of costs, has he taken into account the great wastage in winding these little bobbins? In one instance I remember that the cost of inspection of these small coils was as high as the cost of winding, and the wastage was very large with the fine wires that had to be used. Any method that would get rid of the high cost of winding bobbins of very fine wire would be a great advantage, and these new alloy steels may solve the problem. On the other hand, there is the question of the price of the special steels.

It has to be remembered that when one evolves standard lines which are usually built by the thousand, the total weight of material becomes very considerable; so that one would have to be assured of his supplies of that material before introducing standardization. In conclusion I should like to ask the author how uniform are these steels.

Mr. J. F. Kayser: As the author has indicated, the high cost of magnet steels containing cobalt has undoubtedly prevented their adoption to a very great extent. I really think that their adoption has been still further prevented by the remarkable ignorance of the majority of magnet users concerning the elements of magnetic circuit design. When the author asked me in 1919 if my firm would be prepared to undertake experimental work on high-coercivity cobalt steels and told us of the advantages they would possess, we made inquiries of some half a dozen of the leading electrical concerns in this country and, without exception, they informed us that a cobalt steel would be useless, as ordinary tungsten steel magnets, with a coercive force of 60, were quite permanent enough. The utilization of permanent magnets during the past five years, particularly that resulting from the author's personal work, has shown their attitude to have been quite wrong. It is unfortunate that, in many cases, the choice of a magnet steel is left largely in the hands of a purchasing agent with little or no technical knowledge, and, in many cases, it is quite impossible to get beyond him. If we consider a machine using a tungsten steel permanent magnet, there are three possibilities: (1) The tungsten steel magnet is working economically; (2) it is working too near to the remanence point; and (3) it is working too near to the coercive-force point. In cases (1) and (2) the replacement of the tungsten steel magnet by a high-coercivity cobalt steel magnet will, in every case, lead to a lessening in efficiency, and the instrument must be re-designed to suit the properties of the new steels. In case (3), however, a greater efficiency can, in every case, be obtained by simply substituting the tungsten steel magnet by an exactly similar magnet made from cobalt magnet steel. The loud-speaker is a well-known example of the last. Some few years ago tungsten steel magnets were used, but now practically every loud-speaker on the market is fitted with a cobalt steel magnet.

Mr. E. A. Watson (*in reply*): I quite agree with Prof. Howe as to the general lack of knowledge in regard to permanent magnets, not only as regards the relationship between the magnetic properties of the steel itself, but also as regards the principles underlying the application of permanent magnets and the design of apparatus in which these are incorporated. It is certainly a subject which has been very much neglected in the past, and one to which a great deal more attention might profitably be given; but what I should like to emphasize more than anything else is the importance which attaches to a proper co-ordination between the engineer and the metallurgist. In the past this has been entirely lacking: the engineer, as is confirmed by Prof. Howe's remarks, has a very scanty knowledge of the metallurgy of steel and the various transformations which take place when a piece of magnet steel is hardened, while the metallurgist, on the other hand, has only the vaguest ideas as to magnetic properties and their ultimate meaning. If we are to get any real progress in the improvement of permanent magnets, it will be necessary for the work to be carried out by men who combine both branches of knowledge and who are able to co-ordinate changes in the magnetic properties with the corresponding changes in the metallurgical structure of the steel itself. It is, perhaps, not fully realized that magnetic analysis shows that in the majority of permanent magnets not more than 75 to 80 per cent of the iron can be accounted for as being in the magnetic state, and it is quite likely that well-directed research will find some manner of accounting for at least a considerable proportion of the iron which appears to be present in the non-magnetic condition. At all events a very promising avenue of research work is opened up in this direction—one which has been very little explored and which offers possibilities of making really useful contributions, not only to our knowledge of the materials, but also to their application to the needs of the engineer.

As regards the permanence of these magnets, the whole subject of permanence is one which requires careful research and on which very little really definite is known. Many experiments have been made on the so-called permanence of magnets, but in the majority of cases no proper steps have been taken to discriminate between the many different factors which may cause loss of magnetic power. Quite recently Mr. Evershed has shown * that apart from the ageing due to vibration and temperature changes, there is a further ageing which occurs due to gradual degradation of the steel, and any real work on permanence must separate these two factors before the results can be of real utility. As regards the degradation of the steel, very rough experiments which I have carried out on the air-hardening cobalt-chrome series of steels seem to show that this degradation is very much less pronounced than in the case of a water-hardening tungsten steel, and my own theory is that in any steel—of an air-hardening type—in which the hardening molecule is relatively immobile, degradation due to ageing will be less pronounced than in a water-hardening steel, in which the hardening molecule can move more freely, but I am afraid that at present this is only a conjecture which requires a considerable amount of research before definite statements can be made. My own experience, based in a practical way on the application of cobalt steel magnets for about five years, is that under the same conditions they are at least as permanent as tungsten steels. My firm has had experience of these magnets not only for magnetos, but for small generators, motors and other special classes of apparatus, and we have never had any cases of trouble due to ageing of the magnets, or loss of flux, which could not be accounted for by ill-usage or accidental demagnetization by an external source.

In reply to Mr. Brookes, I am afraid that I cannot agree with his conclusions regarding the relative merits

* See page 725.

of tungsten and chrome steels. I quite agree with him that if a piece of apparatus has been designed for a tungsten steel magnet the direct substitution of chrome steel for tungsten steel, without any change in dimensions, might lead him into difficulties through what he would term "the inferior quality of the steel," but if the slightly lower magnetic values of the chrome steel are recognized and due allowance made for these in proportioning the magnets, I see no reason at all why chrome steel should not give results quite as satisfactory, and I believe that a certain saving in cost might accrue. It is certainly significant that chrome steels should be used so largely in the United States, although I agree that this may be, in part, due to difficulties which have at times occurred in that country in obtaining the requisite supplies of tungsten.

As regards Mr. Brookes's comparison between cobalt and tungsten steels, I think that really we are in agreement, as I would certainly never suggest that a cobalt steel can show any saving, unless the apparatus can be designed around it and advantage taken of the simplification in design due to the shorter length of magnet which can be obtained. In our own case, for instance, although in changing from tungsten to cobalt steel we actually increased the cost of the magnets slightly, the incidental savings obtained and, in particular, the economies in connection with the labour of machining and assembly, were quite sufficient to outweigh the increase in cost due to the change in material. The costs given in the paper for cobalt steel were, as stated, not based on market quotations but on an estimate of what the steels could be produced for under certain conditions, and although at the time the paper was written market quotations were considerably above these figures, at the present time they are substantially in agreement, some prices ruling slightly above the figures and some below. I am pleased to hear that Mr. Brookes reports for the working of tungsten steel considerably lower costs than are quoted in the paper, and I think that if the same good practice were applied to cobalt steels a similar reduction could be expected in this case also, so that this should not affect the comparison to a very great extent.

I am pleased to have Mr. Wright's views, and also those of Dr. Parker Smith, that there is a field for small permanent-magnet motors. They should certainly be more reliable, and the smaller sizes, at all events, should probably be cheaper, even in first cost, than machines with wound field-magnets. There is no difficulty whatever involved in their manufacture, and it should be a line well worth following up. Motors with permanent fields would have the peculiarity that the direction of rotation could be reversed from a distance by merely reversing the polarity of the supply. This might, of course, in certain cases be disadvantageous, as for instance with portable motors, or fans fed through a plug and socket, as care would have to be taken when inserting the plug to ensure that the motor would run in the correct direction. On the other hand, there are many cases in which this would be a distinct advantage, particularly for motors operating a remote-control mechanism, signalling devices, etc.

The use of a salt bath for hardening magnets has considerable possibilities, as it enables quick heating to be obtained, together with a very close control of the temperature. Electrically-heated salt baths are, however, very expensive in first cost, and the cost of upkeep of the bath itself is generally considerable. Modern regenerative gas furnaces are fairly cheap to install and give a reasonable efficiency and very uniform heating. Both types of furnace have, in my experience, been tried for cobalt-chrome magnets, but the gas furnace seems at present to be favoured.

I quite agree with Dr. Parker Smith as to the relative improvement in regard to field losses in smaller machines, as the field losses increase rapidly in proportion as the size of the machine is decreased. With permanent-field machines it is possible to get extremely low no-load losses, and extremely good efficiencies right down to the smallest size. I would instance the case of a small 500-volt motor-generator which we are now making and which will run at 4 000 r.p.m. with a no-load loss of less than 10 watts, a figure which can certainly not be obtained with any wound-field machine. The absence of field loss not only increases the efficiency, but also increases the permissible rating of the machine, in that the heating for a given armature loss is substantially reduced. There might, of course, be losses in these machines if solid pole-shoes were employed, but in all the machines which are described the pole-shoes are made of soft-iron laminations, and in any case the use of magnet steel for a pole-shoe is bad practice and, as far as I know, is never adopted. As regards the allowance for wastage and inspection on the fine-wire coils a certain allowance has been made for this by taking a high value of the copper cost for small gauges of wire, but I could not say for certain whether this would be sufficient to cover the case which Dr. Parker Smith has instanced. I quite agree as to the necessity before making any radical change of ensuring that there would be a continuity of supplies of material, but I think that these steels have now been produced for a sufficient length of time for their supply to become fairly well established, and I believe that there is not likely to be any shortage in raw material for a very long while to come, unless the demand should increase to a very great extent indeed. As regards uniformity, these steels, when made by a reputable maker, are really very uniform indeed, and our records, extending over very nearly 5 years (equal to nearly half a million magnets) show that there has been extremely little variation and an almost entire absence of rejection of material for magnetic defects.

In reply to Mr. Kayser, I too was very much struck with the conservatism of manufacturers and users when these steels were first brought to their attention, and with the ignorance of large users in regard to the principles governing the use of permanent magnets. I am afraid, however, that this was no worse than the conservatism shown by the steelmakers when it was first suggested to them that they should attempt to make cobalt magnet steel; and if it had not been for the enterprise of two firms, of which Mr. Kayser's

was one, the development of cobalt steels in this country might have been delayed for an almost indefinite period. As Mr. Kayser points out, apparatus for the use of cobalt steels must be designed to that end, and the direct substitution of cobalt steel for tungsten steel may, in certain cases, even lead to a worse performance instead of a better. There are, however, cases where the tungsten steel is working disadvantageously and under conditions of excessive demagnetization, and in these cases the substitution will lead to a greater improvement than that corresponding to the properties of the material alone.

ELECTRICITY IN AGRICULTURE.

REPORT OF THE ELECTRICITY IN AGRICULTURE COMMITTEE TO THE COUNCIL.

The Committee was appointed by the Council on the 15th March, 1923, for the purpose of reporting on the following points :—

(*a*) Whether there are any special features in connection with the supply and use of electricity in agriculture which need special attention from the Institution by way of education or propaganda, and, if so, what action the Committee recommend the Council to take.

(*b*) And, for the purpose of making a recommendation :—

(i) To investigate and report upon the actual or probable load factor and annual consumption of farms in this country and elsewhere, and on the capital cost to supply authorities of supply to farms, and to farmers of the machinery for utilizing the supply, and of the economic results likely to be obtained by supply authorities and farmers ;

(ii) To report on the desirability of a permanent Sectional Committee of the Institution for dealing with this question.

The constitution of the Committee is as follows :—

Ll. B. Atkinson (*Chairman*).

C. T. Allan. J. F. Crowley.
J. W. Beauchamp. J. H. Edwards.
S. E. Britton. B. M. Jenkin.
W. R. Cooper. R. Borlase Matthews.
F. A. Sclater.

The Committee has held 5 meetings, one of which was at the farm of Mr. Borlase Matthews, Greater Felcourt, East Grinstead. The Committee have collected from various sources a large amount of information as to the work which has been carried out and the results that have been obtained therefrom, with a view to summarizing these results in the form of a report under the following headings :—

A. Uses to which electricity can be put in agriculture.

(*a*) Electric lighting .. In the house, barn, dairy, poultry house, and other buildings.

(*b*) Motive power .. In the house, barn and dairy, and for water pumping and drainage.
In the field.
The amount likely to be used, the consumption per acre of farm lands.

(*c*) Crop stimulation .. The position.
The amount of electricity likely to be used.

B. Capital Outlay.

(*a*) At the farm .. .. The price at which it will pay the farm to use it.
The financial return on this to the farmer.
The method of providing this outlay.

(*b*) On distribution .. The return on this.
The method of providing this outlay.

C. Existing schemes in operation.

The results.
Lessons therefrom.

D. Steps which might be taken by the Institution.

A. Uses to which Electricity can be put in Agriculture.

(*a*) electric lighting.

Electric light is of considerable assistance to the farmer for the lighting of homesteads, farm yards, poultry houses, and buildings, and particularly for the lighting of farm yards during such operations as threshing. Its use permits the carrying out of certain operations by artificial light which can at present be carried out by

daylight only. The risk of fire, always a serious risk on the farm, is minimized where electricity is employed.

(*b*) MOTIVE POWER.

In the house and barn and dairy; pumping and drainage.—The usual applications of electric motors in agriculture are in the house, barn and dairy. In the former case the motors are generally stationary, either attached to the machines they operate, such as chaff-cutting and corn-grinding machinery, or driving by means of shafting a group of machines, as in dairies. Special types of portable motors suited to farm work have been evolved, particularly on the Continent; these are fitted with suitable reduction gearing for the operation of portable machines and of stationary machines which run too intermittently to justify separate motors.

Table 1 may be taken to be a reasonable estimate of use for an average farm :—

TABLE 1.

Consumption of electricity on a farm of 150 *acres.*

	Kilowatt-hours per annum
Lighting (house)	100
,, (buildings)	150
Motive power, barn and dairy ..	1 500
Heating and cooking	1 500
	3 250

It is useful to consider the consumption of electricity on farms in terms of the annual use in kilowatt-hours (or units) per acre. Table 2 sets out the ascertained figures of use on a number of British farms in a certain supply area.

TABLE 2.

Annual use on 33 *farms in a certain supply area in Great Britain.*

Motors on each farm, average ..	1·4	
Average horse-power	10	
Electric lamps per farm house ..	18	
Electric lamps in buildings ..	18	
Average consumption per annum :—		
Lighting	370	units
Heating	470	units
Power	1 370	units
Average total consumption per annum	2 210	units
Average acreage	230	
Average consumption per acre per annum	9·5	units

Statistics of use on Continental farms which have used an electric supply for several years show a higher consumption than this, averaging 22 units per acre.*

The consumption of electricity per acre of arable land is apparently a function of the fertility of the soil.

* See N. EKWALL: "Electricity in Agriculture," *Transactions of the First World Power Conference*, vol. 4, p. 571; F. A. GABY: "Electrical Service for Rural Districts as provided by the Hydro-Electric Commission of Ontario," ibid., p. 23; F. H. KREBS: "Technical Development and Financial Organization, including Co-operative Schemes for Electricity Supply in Agriculture in Denmark," ibid., p. 242; and R. BORLASE MATTHEWS: "Electro-Farming Economics," ibid., p. 539.

In a very fertile region in the North-East of Germany the consumption averages (without any electric ploughing) 100 units per acre.*

In accordance with the returns for 34 rural districts in Germany, the consumption per acre was 12·5 to 22·5 units for lighting and 27·5 to 42 units for power, a total of 40 to 65·5, or an average of 50 units per acre.†

In the field.—The principal potential use of electric motors is for ploughing, harrowing, etc., and for threshing.

Ploughing.—The application of electricity to ploughing requires motors of from 12 to 125 h.p.,* and is carried out in one of several ways :—

(*a*) By means of electric tractors, fed by a flexible cable carried from a movable pole, which are propelled across the field in a similar manner to petrol or steam tractors.

(*b*) By means of electric tractors propelled by engagement with a chain, which is preferably laid across the field to be ploughed and which is moved forward after each operation.

(*c*) By means of two stationary motors placed one at each side of the field to be ploughed, with a single steel cable traversing the distance between them, the plough being hauled in one direction by one motor and in the other direction by the other motor.

(*d*) By means of a single movable motor placed at one side of the field and a movable anchored pulley at the other, the plough being moved from one side of the field to the other by a steel cable which passes from cable drums on the motor round the pulley.

(*e*) By the Howard or Fisken system, where a single fixed motor is used and, by means of ropes with movable anchored pulleys, the plough or other implement is drawn backwards and forwards on the field.

Systems (*c*) and (*e*) are those which have been most generally adopted. In general these systems of ploughing, as in the case of steam-ploughing on the well-known Fowler system, are applicable to large farms or suitable for employment by contractors who carry out the work on terms for the individual farmer. The problem of electric ploughing, although it is one of the most important on the farm, particularly in view of the growing importance of the sugar-beet industry which requires deep ploughing, cannot be said to be fully solved. It would be the most important load on the farm from the point of view of the power supply engineer. All the arable land on a farm might well be ploughed twice a year, with a consumption of at least 20 units per acre, that is, 40 units per acre per year. Cultivation work on similar lines would take about half this amount, say 20 units per acre, or a total of 60 units per acre; that is, on a farm of 150 acres, half arable, 4 500 units for the field operations alone.

In the absence of any extended experience of electric ploughing in this country comparative costs are not available.

* R. BORLASE MATTHEWS: "Electro-Farming, or the Application of Electricity to Agriculture," *Journal I.E.E.*, 1922, vol. 60, p. 736.

† *Elektrotechnische Zeitschrift*, 1923, vol. 44, p. 633, and *Electrical World*, 1923, vol. 82, p. 125.

The following British figures of cost of other methods may be noted as generally accepted :—

CONTRACT PRICES.

Steam ploughing.—15s. to 25s. per acre, at about 6 in. deep.

Tractor ploughing.—17s. 6d. to 30s. per acre, but this machine is hardly capable of ploughing deep enough on the heavy land without materially adding to the weight of the engine, which is detrimental to corn-producing, as it is apt to make a " pan " which the water cannot penetrate and, consequently, the land is kept in a wet condition very injurious to plant life.

Mole draining.—15s. to 30s. per acre, but varies very much in different parts of the country. In Northamptonshire the drains are made from 5 to 7 yards apart, and in some cases up to 9 or 10 yards. The 7 yards is a good average at from 1 ft. 6 in. to 2 ft. 3 in. in depth. In Essex the drains are very often only 4 yards apart.

Horse ploughing.—20s. to 35s. per acre, according to the nature of the land.

COST OF ELECTRIC PLOUGHING.

The following information has been obtained * as to the price at which electric ploughing is done in France by contract. It will be understood that this represents cost and profit, the price being regulated by competition with horse ploughing.

The figures are given subject to a caution that comparison between the British and French figures must not be taken too literally, as the external and internal values of the franc are very different.

TABLE 3.

Contractors' Price List.

Depth of		Total depth	Price per acre	
Ploughing	Subsoiling			
in.	in.	in.	francs	s. d.†
10–12	5–6	15–18	137	34 3
8–10	5–6	13–16	130	32 6
12–14	—	12–14	127	32
10–12	—	10–12	120	30
6–8	5–6	11–14	120	30
8–10	—	8–10	93	23
6–8	—	6–8	66	16 6

† At 80 francs to the £.

The charge for scuffling to a depth of about 4 inches was 40 fr. (say 10s.) per acre.

In France it is usually reckoned that 10 francs (say 2s. 6d.) per 4 inches of depth is a reasonable charge to pay to contractors for ploughing and subsoiling.

In the 1924 season an electric ploughing set ploughed 1 453 acres (588 hectares). Scuffling was done at the rate of 49½ acres (20 hectares) per day; while a six-furrow plough accomplished 16¾ to 19¾ acres (6 to 8 hectares) in the same time, and a four-furrow deep plough did 12½ acres (5 hectares).

Threshing.—Threshing by means of portable electric motors is another operation which is frequently done on the Continent through contracting firms, who supply a portable transformer for connecting to the distribution system, a cable drum and the necessary large portable motor.

(*c*) CROP STIMULATION.

A good deal of isolated and badly co-ordinated experimental work has been done by various observers as to the stimulation of field crops, from which a general impression only can be received ; it would appear, however, to be established that it is possible in certain cases to increase considerably the quantity and quality of certain crops.

In 1918 a Committee was formed by the Government under Sir John Snell to investigate and report on this question, and under its guidance seven reports * have been prepared covering an examination of the work already done and reporting on experiments both in the field and on plants under pot culture. The results of the field experiments were so conflicting and difficult to reconcile that it has been decided at present to concentrate on pot-culture experiments, with a view to determining as quickly as possible the general conditions of electrification which are favourable, after which field operations will be resumed.

It has been stated in the second Report of the Committee referred to, that increase in yield averaging about 30 per cent had been obtained in field experiments.

The matter has reached a stage which is as yet of no very great practical importance or direct application owing to lack of commercial data and apparatus suitable for placing in the hands of the farmer.

The amount of electricity used for the purpose is insignificant, not amounting to more than about 10 watts per acre, applied for, say, 2 hours a day for one to two months of the growing period.

B. CAPITAL OUTLAY.

(*a*) *At the farm*.—This depends of course on whether the installation at any particular farm is for the purpose of field operations or for lighting, barn and dairy use. Speaking generally, it is probable that as regards the larger field operations the capital outlay is so considerable relative to the amount of use on any particular farm, that except in the case of the largest farms the ploughing and cultivating tackle, as has occurred in the case of steam tackle, will be owned by contractors who will do the work for the farmer. On the other hand, the use of electricity in the house, barn and dairy will be made with machinery and appliances provided by the farmer and the cost may be estimated as follows :—

	£
3 electric motors aggregating 10 h.p., with starting gear and reducing gear ..	60
Electric light, 36 points in house and building	36
Sundry cable and switchgear not included in the lighting	20
	116
Sundry household apparatus	40
	£156

* By the courtesy of M. Hubert, 44, Rue du Louvre, Paris, who ascertained the figures from Les Grands Secteurs Electriques, Versailles.

* Copies may be obtained from the Ministry of Agriculture, 10, Whitehall-place, London, S.W.

Price of electricity obtainable.—As to the price at which it will pay the farmer to use it, there is evidence that farmers will willingly pay for lighting 8d. per unit, for heat 2d., and for power 4d. (electric ploughing from 1d. to 2d.).

Financial return to the farmer.—It is difficult to put any precise figure on the financial return to the farmer. It is probable that on farms employing five men and upwards where other power has not been installed, at least one man can be saved. On smaller farms the advantage would be rather in reducing the number of hours the farmer and his family would have to work and reducing the actual manual toil involved, by reducing risks of fire, or increasing the output of the farm. There is no doubt also that the provision of good lighting in the mornings and evenings of the winter months contributes to saving of waste of materials and of time lost. In the case of farmers owning a considerable head of poultry, it has been established that by lighting the poultry houses in the winter months morning and evening there is an improvement in the average value of the eggs produced, not so much in an increased total number as in their distribution towards the months when daylight is shortest, with a consequent advantage of about 20 per cent in their average value. The result of these various factors is that in the case of an ordinary farm it is estimated by the Committee that these outlays will repay themselves in about four years, after which there will be a return, allowing for repairs, of probably 20 per cent per annum on the money spent on the equipment.

Although this is attractive, the fact has to be faced that farmers have lost a large amount of their capital during the last few years, and that it is probable that in the majority of cases some system of furnishing the equipment on hire-purchase terms would be necessary to encourage the adoption of electricity.

(*b*) *On distribution.*—In this question lies the principal problem of the supply of electricity for agricultural purposes. Whatever the future may hold, there is universal agreement that, in the early stages of establishing a supply network to supply purely agricultural areas with electric power, there will not be a load which will produce a fair return on the expenditure for distributing mains if the development of the uses of electricity is left almost entirely to the initiative of the farmers. The experience in England, France, Italy, Switzerland, Holland, Sweden and Canada leads to the same conclusion and to the general statement that (1) there must exist other sources of income for the transmission system capable of carrying a large, if not the major, part of the capital charges on the investment during the period required for the natural education of the farmers; or (2) there must be an abnormal economic demand for the energy, rendering possible its sale at an abnormal price; or (3) there must exist an abnormal supply of electrical energy which could not otherwise be sold, rendering economic its sale at a price well below the average cost of production, or (4) there must exist social or political reasons why the supply should be furnished at an uneconomic price on account of other advantages to be gained.

In the first category we have such cases as exist in Sweden, where the transmission lines from the waterfalls pass along the valleys in which the agricultural areas are situated, and the lines are easily tapped. In Holland we have the case where lines are put up for distribution to towns and for the purpose of drainage pumps throughout the country, which lines are again easily tapped for agricultural purposes. Or again in Switzerland, where we have a large number of small towns in which are situated semi-domestic industries which in fact are bearing the costs of the transmission and distribution networks used for agricultural purposes.

In the second category we have France, where the shortage of man power stresses the necessity for the supply of motive power and where, in addition, the necessity of maintaining a source of military strength necessitates the maintaining of the agricultural areas at their highest working power and making them as attractive as possible to the population, even at the expense of the State.

The third case is illustrated by Italy, where there is a superabundance of hydraulic power from the Alps in the summer time, the season of the year when the industrial demand is at its lowest and the farming demand at its maximum.

In this country it is probable that the first mentioned consideration will be the predominating influence, though it is likely that the existence of loads other than those provided by agricultural operations or, alternatively, the establishment of industries providing such loads, will be dominant factors so far as rural electric supply is concerned. We find also that in other countries, notably in Scandinavia, Canada and Italy, financial assistance is given by the State towards the provision of rural distribution lines.

C. Existing Schemes in Operation.

In some parts of the Continent the supply of electricity is remunerative. On the other hand, there are many districts where the engineers have not specialized on the rural problem, and these districts are usually unremunerative to the electric supply undertaking. As the farmers become acquainted with the varied uses of electricity, it seems likely that these at present unremunerative districts may become profitable.

When the electrical equipment of railways becomes an accomplished fact there will be a general distribution system in existence which will enable electricity to be carried more widely into the agricultural areas, based upon these main-line transmissions. For the present more tentative methods will have to be adopted; and these for the most part will lie in the direction of extensions from existing plants in towns of moderate size lying within the agricultural districts and where the supply of electric power from such towns will stimulate more intensive methods of farming in the near neighbourhood of such towns and railway systems. Already developments are taking place in this direction. The towns of Altrincham, Aylesbury, Chester, Hereford, Wolverhampton, etc., have already extended or decided to extend their lines into the districts surrounding, while the power supply undertakings in South Wales, Fife, Kilmarnock, etc., are already supplying a number of farmers.

With regard to the actual cost of such distributions, in the cases which have so far been carried out this appears to be higher than a more extended study of the subject will probably suggest. For 6 600-volt overhead bare lines on insulators with creosoted poles carrying three conductors, each No. 10 S.W.G., all to comply with the Electricity Commissioners' Regulations, the cost would lie between £500 and £600 per mile, and it is probable that cheap underground cable systems could be laid in the open country for about the same figure, but the fact remains that the lines erected in agricultural districts in foreign countries have cost much less than this—even as low as £100 per mile in Sweden—and it is probable that a study of the best methods of erecting such lines will lead to a figure of £250 to £500 per mile to comply with the Regulations necessary in this country. A good deal of discussion has taken place as to whether the lines to individual farms should be single-phase or three-phase, and there is little doubt that as regards the lines the single-phase system is cheaper and there is some simplification in transforming and switching gear. On the other hand, the motors are rather larger and more costly and, so far, whatever installations have been completed have been upon the three-phase system.

In order to summarize this part of the Report, it may be well to give the following actual example (in Sweden) obtained by a member of the Committee where conditions were not favourable to a large consumption per acre, as the land was poor. In a rural area of 3 700 acres (of which 1 700 were woodland and waste) about 15 miles of distributors were used to supply 22 farms and 29 other rural customers whose consumption, averaged over several years, was 82 000 units per annum. The return on the capital expended (which was heavy, as the work was carried out during the war) was 5 per cent per annum. The consumption per acre was 22 units, or 5 570 units per mile of distributor. *

D. Steps which might be taken by the Institution.

Although the actual consumption per acre or per farm appears small, yet the total acreage of farm lands in this country is large, being nearly 27 million acres out of the total area of 56 788 366 acres in England, Scotland and Wales, and the supply of electricity to farms, if carried out, would aggregate a very large total, say, under English conditions, 260 million units per annum without electric ploughing or cultivation, and from two to three times this amount if electric ploughing and cultivation as in Continental practice were adopted.

The laying out of the work, the construction of the generating plant and cables or overhead lines, and the supply of plant and accessories would form a very important addition to the activities of the electrical industry. This, added to the social and economic betterment arising therefrom, is of such importance that it is recommended that the Institution should use its influence in promoting this object.

To this end the following are some of the steps that might be taken :—

(1) The appointment of a permanent Committee, to advise the Council of any development arising which they should take note of, or on which they should take action.

(2) The presentation of a memorandum to the Government pointing out the advantages that would arise from a wide distribution of electricity to agricultural counties, and that this should be taken into consideration in fostering schemes of railway electrification.

(3) That a special recommendation should be made to the Government in connection with the provision of financial assistance, either in the form of direct grants or the provision of finance at specially low rates and repayable over long periods, towards the cost of provision of distribution lines in rural areas in districts where there is a prospect of the undertaking becoming profitable in the course of a few years, so as to enable a cheap supply of electricity to be provided for these areas.

(4) That the Institution should take steps to encourage the design by the leading British manufacturing firms of electrical apparatus especially suited to agricultural conditions, such as portable transformers, portable motors for general use, cable reels for enabling temporary connections to be made to such motors, electric ploughing equipments of suitable type, etc.

(5) That in connection therewith the Government should be urged to issue through the Ministry of Agriculture in conjunction with the Electricity Commissioners authoritative leaflets on the subject, showing what has been done and what can and ought to be done by farmers when a supply is available.

(6) That the Institution should offer to co-operate with the Royal Agricultural Society and other agricultural bodies in tests and experimental work, and in formulating a policy for the supply of electricity to the farming population.

(7) That the Institution should take steps to obtain a paper each year on a subject dealing with the applications of electricity to agriculture, and that joint meetings with the Royal Agricultural Society or with one of the other farmers' organizations should be arranged.

(8) That the Institution should take steps to initiate experimental work by or through existing bodies :—

- (*a*) In improving the efficiency of farm implements and machines by redesign of the implements or machines to use the new forms of power available.
- (*b*) In improving the efficiency of methods of crop treatment by means of the new form of power available.
- (*c*) In carrying out investigations that would provide useful data in relation to the application of electricity to agriculture.

(9) That the Institution should take steps to propose Rules for rural distribution networks, overhead and underground. These Rules only to apply to distribution to farms, villages and small industries, leaving other work to be carried out under the existing Regulations as at present approved by the Electricity Commissioners.

* R. Borlase Matthews: "Electro-Farming Economics," *Transactions of the First World Power Conference*, 1924, vol. 4, p. 539.

INSTITUTION NOTES.

Council for the Year 1925–1926.

The scrutineers (Messrs. J. Coxon, P. Dunsheath and W. L. Wreford), appointed at the Ordinary Meeting held on the 23rd April, 1925, in connection with the ballot to fill the vacancies which will occur in the Council on the 30th September next, have reported to the President that 1 428 ballot papers were returned, of which 28 were spoiled, and that the result of the ballot is as follows :—

President: Mr. R. A. Chattock.

Vice-Presidents: Lieut.-Col. K. Edgcumbe, R.E. (T.A.), and Prof. W. M. Thornton, O.B.E., D.Sc.

Hon. Treasurer: Mr. P. D. Tuckett.

Ordinary Members of Council: (Members) Prof. C. L. Fortescue, O.B.E., M.A., Mr. R. W. Paul, Mr. C. Rodgers, O.B.E., B.Sc., and Mr. S. J. Watson; (Associate Members) Mr. R. Grierson, Major E. O. Henrici, R.E. (ret.), and Mr. J. W. T. Walsh, M.A., M.Sc.; (Associate) Mr. E. Leete.

The Council for the year 1925–1926 will therefore be constituted as follows :—

President.

R. A. Chattock.

Past-Presidents.

A. Siemens.
Col. R. E. Crompton, C.B.
Sir Henry Mance, LL.D., C.I.E.
J. Swinburne, F.R.S.
Sir R. T. Glazebrook, K.C.B., D.Sc., F.R.S.
W. M. Mordey.
S. Z. de Ferranti, D.Sc.
Sir John Snell, G.B.E.
C. P. Sparks, C.B.E.
R. T. Smith.
Ll. B. Atkinson.
J. S. Highfield.
F. Gill, O.B.E.
A. Russell, M.A., D.Sc., LL.D., F.R.S.
W. B. Woodhouse.

Vice-Presidents.

Sir James Devonshire, K.B.E.
Lieut.-Col. K. Edgcumbe, R.E. (T.A.).
A. Page.
Prof. W. M. Thornton, O.B.E., D.Sc.

Honorary Treasurer.

P. D. Tuckett.

Ordinary Members of Council.

Captain J. M. Donaldson, M.C.
The Viscount Falmouth.
Prof. C. L. Fortescue, O.B.E., M.A.
R. Grierson.
Major E. O. Henrici, R.E. (ret.).
W. E. Highfield.
Herbert Jones.
E. Leete.
Sir B. Longbottom.
S. W. Melsom.
G. W. Partridge.
R. W. Paul.
Col. T. F. Purves, O.B.E.
C. Rodgers, O.B.E., B.Sc.
P. Rosling.
E. H. Shaughnessy, O.B.E.
J. W. T. Walsh, M.A., M.Sc.
S. J. Watson.

And

the Chairman and immediate Past-Chairman of each Local Centre.

Regulations for the Electrical Equipment of Buildings.

The Council have approved a number of alterations to the Eighth Edition of the above. Copies can be obtained from the Secretary for insertion in existing copies of the Regulations.

Associate Membership Examination.

The next Examination will be held on the 29th, 30th and 31st October, 1925. Candidates must be either Students or Graduates of the Institution or have lodged with the Secretary a duly completed form "E" for election as Associate Member. Entry forms for the Examination, which must be completed and returned by the 1st September, and particulars regarding election to membership of the Institution may be had on application to the Secretary.

Coopers Hill War Memorial Prize.

The triennial award of the above Prize falls this year to the Council of the Institution of Electrical Engineers, who have selected for the subject of competitive monographs "The Applications of Electricity to Metalliferous Mining." Intending competitors are reminded that the latest date for submitting their MSS. is the 31st October, 1925. The award for 1925 is limited to Corporate Members of the Institution who were under 30 years of age on the 1st January, 1925. Full particulars can be obtained on application to the Secretary of the Institution.

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 June–25 July, 1925:—

	£	s.	d.
Arrowsmith, S. J (London)		5	0
Beaton, C. A. (London)		5	0
Brumwell, W. (Parkstone)		7	6*
Burrows, G. B. (Manchester)		10	0*
Catterson-Smith, J. K. (Bangalore)	1	0	0
Chapple, F. J. (Liversedge)		10	0
Franklin, E. S. (Bath)		13	0
Green, F. W. (Melbourne, Australia)		10	6*
Griffin, J. G. (Hatfield)		10	0
Hamson, P. (London)		2	6
Hurle, V. R. (Swindon)		5	0
King, C. D. (London)		5	0
Lawson, F. A. (London)		5	0
Macnaughton, A. I. (Airdrie)		5	0
Needes, E. C. (Pontypridd)		5	0*
Palmer, W. G. (Sheffield)		10	6
Redman, W. (Shipley)		5	0
Reuben, E. A. (Nagpur, India)		2	6
Rose, W. C. (London)		2	6
Saltren-Willett, C. G. (Cardiff)		5	0
Samuel, R. P. (Colchester)		5	0*
Sen, A. K. (Jamshedpur, India)		2	6
Shaw, J. H. (Dublin)		5	0
Slorach, J. W. (Hamilton)		5	0
Taylor, F. W. (Oldham)		1	0
Tumilty, H. G. (Dovercourt Bay)		8	6
Turner, W. (Sheffield)		5	0
Wharfe, L. E. (Pontefract)		7	6
Wigg, C. B. (London)	1	0	0*
Williams, Edward (London)		5	0*
Williams, J. (Manchester)		2	6
Williams, W. R. (Garnant, Carmarthen)	1	1	0

* Annual Subscriptions.

ELECTRICITY SUPPLY TARIFFS: THEIR SIMPLIFICATION BY DISCRIMINATION.

By G. WILKINSON, Member, and R. McCOURT.

(*Paper first received 2nd February, and in final form 2nd March, 1925; read before* THE INSTITUTION *2nd April, 1925.*)

SUMMARY.

In the fourth annual report of the Electricity Commissioners, reference is made to the rateable-value system of charging for supply, the limitations of that form of tariff, and its unsuitability for general application. In this paper the authors suggest a two-part tariff, the first charge being based upon an agreed maximum demand in watts for which a definite number of units at 8d. per unit are charged per kilowatt of demand, and all over that number are charged at a low price per unit. Being based on the electrical demand of the consumers, this tariff can be offered to all classes of consumers; thus equity is secured in every instance.

Provision is made whereby the consumer may exceed his maximum demand; but should he do so the consumption is recorded on a second dial, the units thus registered being charged for at a higher rate. A simple, reliable, effective mechanism for automatically changing the record from one dial to the other is described.

Attention is directed to the important part which diversity and load factor play in framing tariffs.

It is now generally acknowledged that a full and free use of electricity is of vital importance to the industrial and social life of the community, and prominent leaders of all political parties have expressed their conviction that an abundant and cheap supply of electricity would greatly assist in the alleviation of the many social ills from which the State is at present suffering.

To achieve this object of a more extended, if not universal, use of electricity by all classes is the life work of all electrical engineers, and whilst improvements in the efficiency of the generating, distributing and current-consuming apparatus are of the utmost interest to them, there is no doubt that to the layman or the man in the street the most important point is the price per unit asked for his electricity service.

The consumer is to-day offered a bewildering choice of tariffs from which to select, and he has frequently expressed himself in very emphatic terms about their complexity and the difficulty experienced in making a choice. If electricity could be sold on the same terms as flour, tea, sugar, etc., viz. at a flat rate per unit with varying discounts according to quantity used, the average consumer would be better satisfied and much more amenable to suggestions that he should increase his use of electricity by purchasing other current-consuming apparatus in addition to electric lamps. Unfortunately we cannot get our tariffs framed on quite such simple lines, but the authors maintain that the sale of electricity can be made much less complicated than it is at present, while providing equity not only between the supply undertaking and its consumers, but also between the various classes of consumers themselves, both desirable characteristics which are lacking in many of the tariffs at present in vogue. Until the price charged to each consumer bears a definite and reasonable ratio to the profit made on his supply, the question of tariffs cannot be regarded as being satisfactorily solved.

There have been many papers and discussions on tariffs since the historic occasion when the late Dr. John Hopkinson first laid down the principle that each consumer should bear his proportion of the cost of the standing charges involved in providing his demand, and from the many systems evolved there has gradually crystallized the general consensus of opinion that a two-part tariff is the most equitable method of charging for electricity consumed.

Probably the most popular two-part tariff is the well-known "rateable value" system, which consists of a fixed charge, based on the rateable value of the premises, plus a low price per unit for all electricity used. The obvious objection to this tariff is, of course, that it bears no relation whatever to the electrical demand made by the consumer on the supply undertaking. Two consumers may, and frequently do, have premises which are equally assessed for rating purposes, and their respective electrical demands on the supply undertaking may be, and often are, very unequal, but they both have to pay the same fixed charge. Another objection to the "rateable value" system is that it is not applicable to every class of consumer but has been devised for and adopted by the domestic consumer only, because, generally speaking, he alone derives benefit from it as compared with other tariffs. The shopkeeper, the manufacturer, the hotel-keeper and all highly rated consumers are penalized, whilst the occupiers of all low-rated premises are subsidized if charged for electricity on the rateable-value system.

Another two-part method which is coming into vogue in some localities is to substitute floor area for rateable value as a basis for the fixed charge. This method, however, presents the same disadvantages and inequalities as the rateable-value system.

The authors submit, therefore, that while a two-part tariff is the best for stimulating the increased use of electricity, the fixed charge should be based on the electrical requirements of the consumer in watts or kilowatts, and on this alone. The consumer's electrical requirements will be classified on the basis outlined later in this paper at a definite amount for which he pays in the form of a minimum number of units at 8d. per unit and the residue at a low price per unit. Thus the average price will decrease as the hours of use increase during the 24 hours of the day; and only if, and when, he exceeds that agreed demand would a higher

rate be charged. Such a tariff can be offered to all classes of consumers without distinction, since it is based on their electrical requirements—the only sound and equitable basis for negotiation between supplier and consumer. This principle is at the root of the Wright maximum-demand system, but the authors' experience, in common with that of all central station engineers, has been that consumers do not understand its mode of operation, and when a consumer of any commodity does not understand the system on which he is charged he often has a suspicion that advantage is being taken of his ignorance. Under the proposed system the consumer can ascertain his position and liability unaided at any time, by observing his meter readings.

For such a tariff a cheap and reliable mechanism is required which, while limiting the consumer to his declared maximum supply at a cheap rate, will also automatically secure a higher rate of tariff during the time when he exceeds, either by accident or design, his declared maximum demand. Thus an equitable tariff is at once available—a tariff equitable not only as between the supply undertaking and individual consumers but also as between consumer and consumer, and this regardless of the particular times at which the supply is taken or the purposes to which is is applied.

The authors claim that they have devised a system and designed a simple and reliable instrument by which these substantial advantages can be obtained and the accruing growth of business secured. Briefly the *modus operandi* is as follows: The consumer, instead of having to wait until the end of the quarter or half-year to learn the amount of his more or less variable demand, with the assistance of the supply undertaking assesses himself to take a fixed number of watts as a normal maximum of his requirements, and for this demand he pays a fixed quarterly charge per kilowatt demanded at 8d. per unit, according to his classification. A two-rate meter is installed, on one dial of which all the current used under normal conditions, including the pro rata number of units at 8d., are recorded; after this deduction the residue is charged at the low price per unit. Should he at any time exceed the amount of this pre-arranged demand the mechanism called the "discriminator" comes into operation and automatically transfers the record of current consumed to the second dial, the units registered on that dial being charged for at a higher rate. It follows, therefore, that a consumer will use every means not to exceed his agreed demand, while at the same time he will endeavour to keep his demand as high as possible within the low-rate supply limit, thus giving the supply authority a much better load curve.

To assist the consumer and give him visible indication when he is exceeding his declared maximum demand a neon lamp or lamps may, if desired, be arranged at prominent positions and illuminated through the action of the "discriminator" changing the record of current consumed from the low-rate dial to the high-rate dial.

The mechanism to carry out the objects named by the authors must be of the simplest character, low in first cost, and entirely dependable in service for long periods without requiring attention at any time.

An Equitable and Simple Electricity Tariff for all Purposes.

The authors propose for this tariff an electricity meter of any dependable make fitted with two dials, one of which records the normal consumption and the other all units consumed under abnormal conditions.

The ordinary method of using such a two-rate meter is to have a time clock in connection with it which, by means of a shunt coil and a magnetic device, transfers the record to the second dial during light-load hours, all such consumption being charged at a reduced rate per unit, and restores the record to the original dial at an arranged hour, varying according to the time of the year. Obviously such a method can give only a very rough approximation to the actual cost and corresponding sale value of the units so supplied. In some cases the selling price compared with the cost of production will be excessive, whilst in others the price obtained may be actually below cost. One grave objection to this method of use lies in the employment of expensive and delicate clockwork mechanism. The authors have had wide and long experience with clockwork mechanisms and are convinced that an extensive use of expensive clockwork in connection with supply meters is a retrograde step, since the clockwork requires not only frequent winding but also considerable attention and repairs due to the unsuitable conditions under which it has to work.

The authors use the two recording dials in an entirely different manner; one dial, which is always in use under normal conditions, is called the "low rate" dial, and the other, which comes into use only when the consumer by design or accident exceeds his contract with the supply undertaking by imposing a heavier maximum load than he is entitled to under the terms of his agreement, is for convenience termed the "high rate" dial. When the load is reduced within the limits of the consumer's contract the record is automatically restored to the "low rate" dial.

These changes are effected in an entirely reliable and simple way by the mechanism called the "discriminator." This consists of a small coil or solenoid of few turns in series with the main circuit of the meter; within the solenoid is a light iron core or its equivalent shackled to the rocking bar operating either one or other of the dials referred to, according to its position. Normally, by reason of its own weight or otherwise, the rocking bar maintains the recording gear in circuit with the "low rate" dial, but, should the load at any time exceed the amount contracted for, the increased current in the series coil is strong enough to rock the bar, thereby disconnecting the "low rate" dial train and bringing into use the train operating the "high rate" dial, upon which the consumption is then recorded until the load is reduced to within the limits of the contract, when its record is automatically restored to the "low rate" dial. The units recorded on the "high rate" dial are charged for at a price sufficiently high to deter the consumer from exceeding the terms of his contract.

For instance, if after an initial fixed charge of 8d. per unit per kW demanded, for the first 45 units per quarter, the normal charge is fixed at ½d. per unit,

bringing the average price for all purposes to 0·809d. per unit on a 12-hour load factor, or 0·666d. per unit on a 24-hour load factor, a charge of 6d. per unit for all units recorded on the "high rate" dial would be ample to secure a fairly rigid adherence to the terms of the supply contract.

In a uniform tariff meter of this character it is of the utmost importance to obtain simplicity and cheapness, together with entire reliability of operation.

Figs. 1 and 2 show how these features are secured. Again, it is essential that the change-over from the "low rate" to the "high rate" dial shall be prompt and accurate without danger of the operating gear taking a neutral position clear of both recording mechanisms.

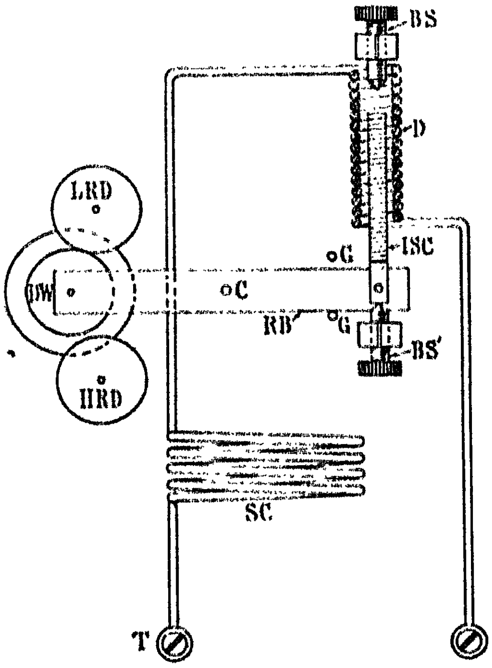


FIG. 1.—Diagram of connections of uniform tariff meter, a.c. type.

SC = meter series coil
D = discriminator
ISC = iron spiral coil with solid end
BS, BS′ = adjustable magnetic screws
RB = rocking-bar carrying driving wheel DW
LRD = low-rate dial train wheel
HRD = high-rate dial train wheel
C = rocking-bar turning centre
T, T′ = meter terminals
G, G = rocking-bar stops

This is achieved by the adjustable magnetic brakes at the top and bottom, in the form of steel screws as shown. These screws are set to positions which in the one case restrain the iron core from being lifted by the solenoid until the maximum load contracted for is exceeded, when the current in the solenoid is able to overcome the magnetic brake; thus there is the ample stored energy in the movable element to carry the gear promptly and definitely into train with the "high rate" dial. The restoration of the record from the "high rate" dial to the "low rate" dial when the load is reduced, is equally prompt and reliable, but the load to effect this must be reduced to a little less than the maximum load allowable under the contract.

The uniform-tariff meter as described is simpler and contains fewer parts than the ordinary two-rate meter, and no time clock whatever is necessary in connection therewith; also it is much less expensive and complicated than a maximum-demand tariff, which calls for two separate instruments and does not allow of the equitable grading of charges obtainable with the uniform-tariff meter.

The authors are of opinion that the fixed-charge part of the tariff should be built up on the basis of a quarterly charge at, say, 8d. per unit for a definite number of units per kW of demand, according to classification, and all over this number registered on the "low rate" dial to be charged for at, say, 1d., ¾d. or ½d. per unit according to the size of the undertaking and the local conditions under which the supply is furnished, all the units registered on the "high rate" dial to be charged for at, say, 6d. per unit. The charts in Fig. 3 show

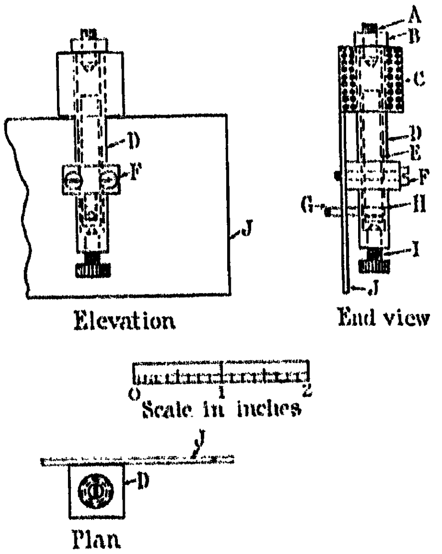


FIG. 2.—Actual fitment in meter.

A = top magnetic screw
B = bush carrying screw A
C = operating coil
D = carrier of insulating material
E = magnetic core
F = fixing screws
G = pin operating rocking bar
H = hole in core engaging pin G
I = bottom magnetic screw
J = back plate of counter gear frame

that the consumer is encouraged to make long-hour use of his agreed demand without exceeding it.

CLASSIFICATION.

The authors claim that the time has come when, in framing tariffs, supply undertakings must take more accurate account than they have hitherto done of diversity factor, not alone of consumers but of the different classes of use which the consumers make of their supply. The importance of taking diversity factor into account is realized when one remembers that the recorded maximum demand on the generators over a given period of time is always less than the aggregate demand of the consumers during the same time, while the figures

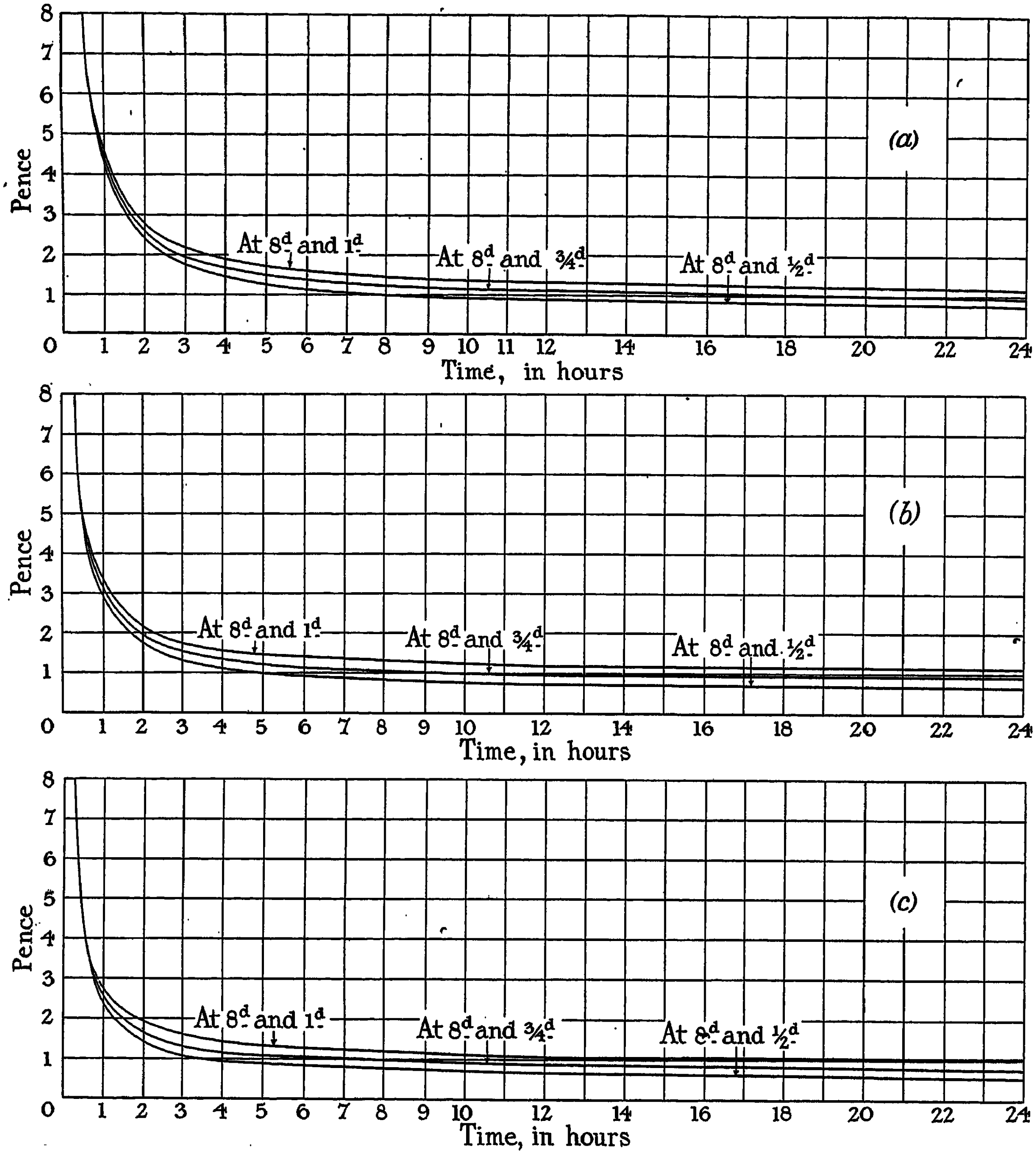


FIG. 3.—Average price obtained per kilowatt-hour at 8d. per unit.

(a) At 45 hours per quarter				(b) At 30 hours per quarter			(c) At 22·5 hours per quarter		
At 8d. and 1d.		At 8d. and ¾d.	At 8d. and ½d.	At 8d. and 1d.	At 8d. and ¾d.	At 8d. and ½d.	At 8d. and 1d.	At 8d. and ¾d.	At 8d. and ½d.
hours	d.	d.	d.	d.	d.	d.	d.	d.	d.
1	4·461	4·335	4·206	3·307	3·14	2·97	2·73	2·54	2·35
2	2·731	2·543	2·354	2·153	1·94	1·75	1·86	1·64	1·43
3	2·154	1·951	1·743	1·76	1·54	1·32	1·54	1·32	1·11
4	1·846	1·671	1·426	1·56	1·34	1·11	1·43	1·16	0·963
5	1·670	1·467	1·241	1·46	1·22	0·994	1·34	1·108	0·87
6	1·576	1·347	1·118	1·42	1·14	0·912	1·28	1·04	0·809
12	1·269	1·048	0·809	1·19	0·967	0·707	1·14	0·899	0·656
24	1·144	0·899	0·666	1·09	0·854	0·603	1·06	0·769	0·577

indicating diversity factor in relation to the various uses made of the supply during each day have a wide range. Furthermore, the minimum number of units so charged will naturally vary with the character and size of works, the nature and class of the business, and the cost of coal, labour and other conditions and commodities involved in the business.

Under ordinary conditions equity calls for the division of the consumers into at least three classes, viz. factory and workshop, business, and domestic, and under these heads the examination of their various uses of the supply from the standpoint of diversity factor is interesting. Probably in numbers of cases they will work out approximately as in the accompanying table.

each consumer to increase the number of hours per day during which he uses electricity, the secondary rate per unit must be low. Briefly stated, a tariff such as that advocated by the authors will give the strongest possible incentive to the consumers to increase their hours of use and decrease their maximum demand on the supply station.

It will be clearly recognized that a simple and rapidly falling tariff as described constitutes the best possible stimulus for the introduction of additional electrical devices. Both the business man and the householder immediately begin to devise methods of long-hour use, and find it in many cases advantageous to introduce power absorbers of the nature of hot-water storage

Class	Lighting	Power	Heat	Proportion of total output	Diversity factor
				per cent	
(A) Factory and workshop	1	2	Nil	20	1 } Say for a town of less than 50 000 population
(B) Business	1	2	3	30	2
(C) Domestic	2	3	9	50	4·6
Average	$1\frac{1}{3}$	$2\frac{1}{3}$	4	100	—

Final average of (A), (B) and (C) = 2·5.

In the case of lighting in factories and workshops the diversity factor may seldom be more than unity, but in the case of domestic supply it is almost certain to be frequently more than 2. Similarly in the case of power in a factory the diversity factor may be less than 2, but in business premises it is likely to be more than 2. In the case of a present-day factory or workshop the amount of electric heating, which includes cooking, is so small that it may be neglected, whilst among the domestic consumers it is now fairly well established, and confirmed in Mr. S. C. Hurry's recent paper before the British Electrical Development Association, which summarizes the replies from 20 public supply engineers, that the cooking load has a diversity factor of 9 to 10. Thus the figure of 9 which we have taken is justified. By arranging the various uses of the different consumers we arrive at an average diversity factor of 2·5.

Diversity factor is, however, not the only consideration in framing a tariff, as the load factor is very important from the supplier's point of view. To obtain a high load factor is the object which attracts us all, and an attractive tariff will help to improve the load factor both of the individual consumer and of the undertaking from which he obtains his supply. If, therefore, a tariff is arranged in which the standing charges are secured based on the demand required, and which also encourages

not only for culinary and lavatory use but also for room-heating purposes. The authors suggest also that in numbers of instances a sound case can be made out for the introduction and use of storage batteries deriving their charging current from the supply undertaking during the hours of light load and discharging their current on heavy load, thus keeping down the maximum demand and thereby reducing the number of units chargeable at 8d. In some cases by these and kindred devices it will be possible to approximate to a 24-hour or 100 per cent load factor and thus obtain the supply at an average rate not greatly in excess of the actual cost of production to the supply undertaking.

This means that a considerable proportion of the capital-outlay burden will be transferred from the supply undertaking to the consumer; to the consumer it will mean vastly improved social amenities in the shape of automatic hot-water supply, thermostatically controlled room-heating, ample light at cheap rates, electric cooking, washing and other labour-saving devices, while to the manufacturer it will mean a greatly increased demand for his commodities with growing prosperity and happiness all round. Incidentally, but by no means an insignificant item, in big towns and cities it will secure a clearer and largely fog-free atmosphere.

[The discussion on this paper will be found on page 856.]

ELECTRICITY SUPPLY TARIFFS.

By H. M. Sayers, Member.

(*Paper received 9th March, and read before* The Institution *2nd April,* 1925.)

Summary.

The paper deals with tariffs for domestic supply.

A rational and practicable basis of charging is:—Cost, plus a reasonable return on the capital employed.

Distribution costs are very heavy; their reduction requires more attention than it has received.

"Copper cost" of distribution is largely (and generating cost somewhat) dependent upon the form factor (shape of load diagram), as well as upon the load factor of each section of a distribution system. This and other distribution costs do not follow the same laws as the costs of generation in respect to load factor and form factor. The cost of "units unaccounted for" increases at each step; it is necessary to measure them, and to take the necessary steps to reduce them to a minimum. A good load factor in one section does not compensate for a poor load factor in another.

The consumers on any distribution network could be commercially charged a uniform flat rate determined by their aggregate load factor (i.e. taking into account the diversity factor among themselves), but this would penalize some to the advantage of others.

The suggestion is that domestic tariffs should consist of a number of flat rates, based on a classification of consumers according to their loads and their class diversity factor and load factor. This will encourage domestic loads of a desirable nature.

A limitation of lighting loads in proportion to other loads may be necessary at present, but domestic lighting will probably cease to be a predominant feature of the peak loads, as cooking, heating, and other domestic uses become more general.

This discussion of electricity supply tariffs assumes that a rational, practical tariff must be based upon costs.

The principle of charging on the basis of the value of the service (what the traffic will bear) can be followed only to a very limited extent in the case of a public utility service carried on in the presence of competitive agencies and under statutory regulations which forbid "preference" and fix maximum prices.

A second assumption is that it is an obligation of a statutory undertaker to meet the demands of the public to the fullest extent practicable—subject to obtaining a reasonable remuneration for the capital, skill, and labour employed in giving the supply. This obligation is rather explicit in the law relating to electricity supply.

The practice of basing tariffs upon costs is widely adopted for supplies to factories, etc., and for traction and bulk supplies to authorized distributors. It is shown by the prevalence of coal clauses, two-part tariffs, power-factor charges, and, in many contracts, by provisions for the periodical revision of prices, subject to arbitration, where the arbitrator can do no other than satisfy himself what is the cost of the supply, including capital charges and a reasonable profit.

In these large-consumer classes an upper limit of price is given by the cost to the consumer of generating his own supply, including in the cost the consumer's estimate of the cost of the capital invested, space occupied, additional cost and trouble of management; while the prohibition of preference means that large consumers generally get the reflected benefit of those who are best placed to produce for themselves. For such industrial consumers the load conditions can be ascertained pretty closely, and the consequent cost of the supply can be estimated with fair accuracy. The practice has met with brilliant success.

For domestic consumers in general the case is very different. The individual capital costs of services and meters, and of working costs such as meter reading and maintenance, accounting and collecting, are relatively high—highest for the smallest consumers. The load characteristics of domestic consumers vary widely. They are all lighting consumers—the majority nothing else—but electric ironing, cooking, heating, washing, and small-machine driving are being slowly adopted, and the load characteristics vary with the extent to which these other uses prevail. Which tariff (or tariffs) to adopt for such domestic supplies is the important question to-day.

Accepting the principle that a rational, remunerative tariff—or tariff scale—must be based on costs, it is proposed to examine the elements of the cost of supply and how these vary with load characteristics; and to submit that a tariff based on a classification of domestic consumers by their class load-characteristics will attract consumers, improve the general load character of the undertaking, increase the return on the invested capital and meet general public interests.

At present, domestic supplies are mainly for lighting. Where the load is of this character the load factor is of the order of from 10 to 12 per cent; or the yearly output is the equivalent of the maximum demand used for from 900 to 1 100 hours per annum. Under these conditions the capital charges of a municipal undertaking—which includes the minimum guaranteed return that will attract capital—are generally greater than the working costs. In such a case, to raise the load factor of the system from 10 to 30 per cent will reduce the costs per units sold by at least one-third all round, and probably more.

The influence of load factor upon generating costs has been studied in great detail, and it is well known that for any given station the curve of costs plotted against output in a given period resembles the Willans steam-consumption line for a particular engine, or the

Parsons coal-consumption line for a particular battery of boilers. It is a straight line which cuts the cost axis at some amount per period for zero output. If this is tested for any station it will be found that the intercept on the cost axis for zero load is not constant; it varies with the maximum load reached during the period. For example, the zero output cost in June will be lower than in December for any British station with a predominant lighting load; lower in gross amount, but higher per kilowatt of maximum demand and per unit sent out. For a station with a predominant industrial demand, but still getting its peak in mid-winter from superposed lighting and factory loads, the June zero-output cost-intercept is also lower than the December figure, but the costs per kilowatt of maximum demand and per unit sent out are lower.

The capital charges per period do not vary with either the maximum load or the output. They are a constant addition to the zero-output working-cost.

Some other points about generating costs which it is necessary to make here are: First, that while generating-station costs are not directly affected by diversity factor, but by the load factor which is the resultant of all the loads and the diversity factor among them, yet the diversity factor does affect the correct allocation of station capital charges to different loads. A very simple (and quite unpractical) example is, that if each of four consumers gives a station load of 1 000 kW for 6 hours per day without overlap, each of the four should pay one-fourth of the capital charges (including profits) proper to a load of 1 000 kW; whilst if one consumer gives a station load of 1 000 kW for 24 hours every day, he should pay the whole of the capital charges on 1 000 kW. A uniform kW charge in a two-part tariff would not be equitable as between the two cases. As a more practical example, an ice-making plant which runs only during the summer months may be equitably debited with, say, half the annual kW charge relating to the station, the other half being met from, say, the heating load utilizing the same generating capacity in mid-winter.

The effect of load characteristics upon distributing costs has not been scrutinized so closely as the effect upon generating costs. It is more complex, and the elements necessary for evaluation are not so readily ascertained. The subject requires greater consideration. The fact that distribution costs and charges are often from two to four times the costs of generation per unit sold shows that there is ample room for investigation and improvement.

The relations between distribution costs and load characteristics are not of the same form as those between generation costs and load characteristics, and they are different for different parts of the distributing layout. For example, let us take the ohmic losses in the mains. Any main has the maximum physical efficiency of 100 per cent at the useless load of zero, when its commercial efficiency is negative; whereas the physical efficiency of generating plant is zero at zero output, and a maximum at some load not far from that of maximum commercial efficiency—the largest output rate which can be carried without damage to any part.

The maximum commercial efficiency of a main is given by the Kelvin relation. Ohmic losses vary with the square of the instantaneous load. Consequently, the distribution of the loads in time has a large influence upon their proportion to the energy delivered, and upon the loading for minimum cost per unit delivered. If a given number of units is delivered through a given main in a given period—say one day—to a steady load lasting 6 hours per day, the rate of ohmic losses is 16 times as great as for a steady 24-hour load giving the same delivery; or, in other words, the units lost in transmission will be four times as great in the 6-hour case as in the 24-hour case.

Increased transmission cost due to the lower load factor cannot be entirely avoided by increasing the copper section of the main. For suppose that the copper section complies with the Kelvin relation for the 24-hour steady load (i.e. copper capital charges equal the cost of the losses), then to maintain that equality the copper section must be doubled for the 6-hour load, when the ohmic losses will also be double those for the 24-hour load. So the maximum transmission economy for the 6-hour load will give double the cost per unit delivered of the 24-hour load, for both copper capital charges and ohmic losses.

Applying this to the hypothetical comparison of one consumer giving the station a 1 000 kW load for 24 hours, with four consumers each giving that load for 6 hours per day without overlap, it appears at once that the distribution costs in the two cases can only be identical if all four consumers are supplied through the same length and size of main as the one consumer, and that the four services are taken from the same point. Suppose that they are not so located but that a main has to be laid to each, of the same length as to the one consumer. Then each main will have a 25 per cent load factor. It will, if designed for maximum economy, have half the copper section and twice the ohmic losses and voltage-drop of the economic main for the single 24-hour consumer; so that the total copper employed, the capital charges upon it, and the annual losses in the four mains, will each be twice as great as for the main supplying the 24-hour consumer. Hence the kW charge *qua* distribution for the 25 per cent load factor 6-hour consumers should be twice that for the 100 per cent load factor 24-hour consumer.

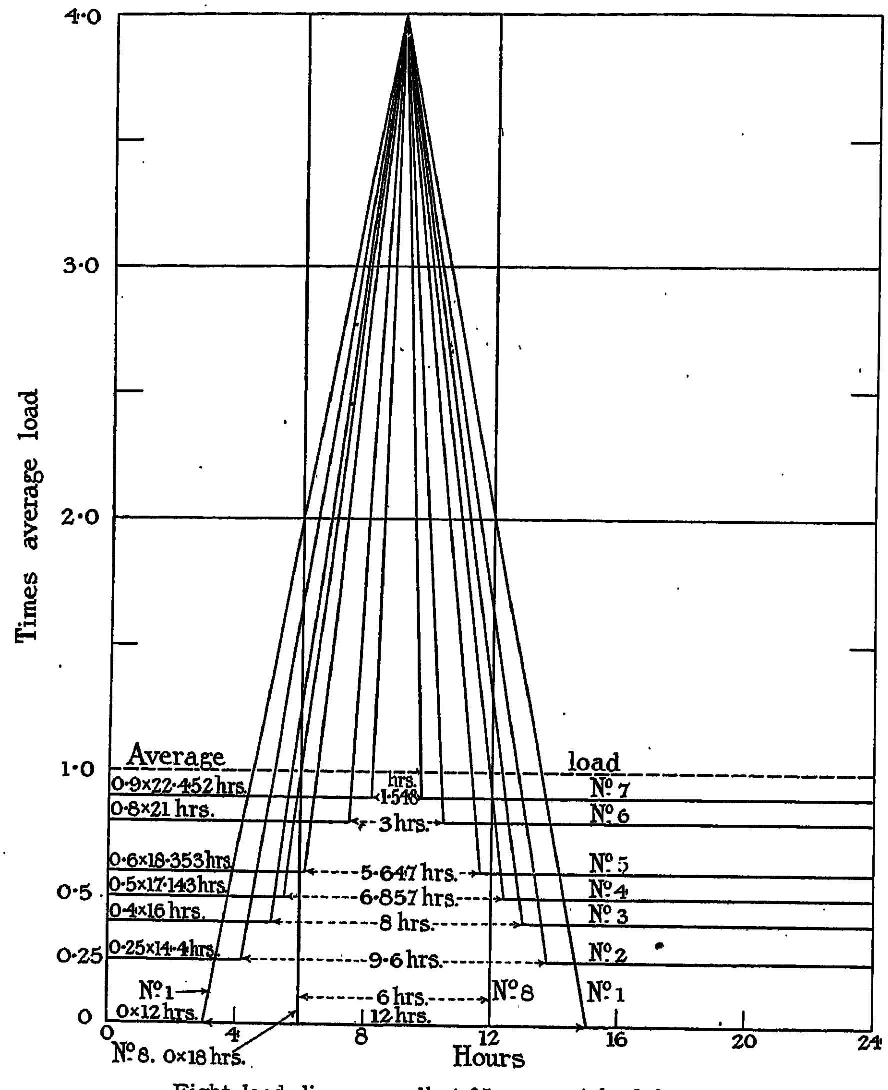
It will be seen that if the condition postulated of equal load at the station busbars is observed, the units sold to the four consumers will be fewer than the units sold to the one, by the difference in mains losses; or, if the units sold are the same, the station load and the units generated will be greater for the four 6-hour consumers than for the one 24-hour consumer. The station costs per unit sold will be greater for the four than for the one, and the extra cost is a distribution cost, though shown in the station expenditure.

The extra station cost could be avoided by making each of the four mains the same size as the one 24-hour main. Evidently the capital charges on the copper would then be four times as great per unit sold, instead of twice as great, and the mains losses would be kept at the same amount; in other words, instead of equality of the copper capital charges and the cost of copper losses, the capital charges will be four times the cost

of the losses, and the total of the two will be in the ratio of 5 to 2, compared with the total for the single 24-hour consumer, instead of in the ratio of 4 to 2 with the correct economical section.

This example illustrates the fact that diversity factor among loads has its full effect on the load factor of the station supplying them, but it only improves the load factor on the distribution side if the diverse loads are supplied through the same mains. The cost of distribution through any one feeder or section of a distribution system with a 10 per cent load factor is not in the least reduced by the existence of other sections enjoying a 50 per cent load factor. But if a number of sections are supplied through one feeder, the load factor of the feeder will be the better for any diversity factor existing between the sections.

Diversity factor between loads means a difference in the time incidence of the individual maximum demands. Numerically it is the ratio between the sum of the individual maximum loads (whatever the time at which they may occur) and the maximum of the combined loads. If the individual maxima are simultaneous the ratio is unity. If they are not simultaneous the combined maximum will be less than the sum of the individuals, and the quotient of the larger divided by the smaller quantity will be greater than unity. The combined load factor is equal to the separate load factor multiplied by this ratio—the diversity factor—where separate load factor means the ratio of the units delivered during a specified time to the product of the sum of the individual loads and the time.



Eight load diagrams, all at 25 per cent load factor.

The costs of transmission depend upon the form of the load diagram as well as upon the load factor. It may indeed be said that the form factor is the more important. For any load factor the worst condition for cost of transmission is that of a steady load for the load factor percentage of the load period, and zero load for the remainder of the period, i.e. a rectangular load diagram standing on the zero line. A 25 per cent load factor will be shown by a load diagram with a steady

load for 6 hours per day and no load for 18 hours per day, when the transmission costs per unit delivered will be twice as great as for a steady 24-hour delivery, or 100 per cent load factor. For any load factor whatever, the maximum multiplier or "form factor" is the square root of the reciprocal of the load factor. For any time distribution of load other than that represented by a rectangular load diagram—maximum load or no load—the form factor lies between that maximum and unity, but can only be unity for 100 per cent load factor. The average load over the whole periodic time multiplied by the form factor is the R.M.S. load, and is the value to be used for finding the most economical copper geometry of the triangle, the slopes on either side of the apex may be any pair fulfilling the condition that they cut the time base 12 hours apart and meet at four times the average load taken over 24 hours.)

Actual load diagrams are rarely of simple form and it is therefore generally necessary to measure, square, and take the mean square of a sufficient number of ordinates, in order to get the form factor; so that to calculate economical copper sections one must possess or forecast a load diagram.

Calling the ohmic losses the working costs of the main, both the copper capital charges and the working costs increase as the R.M.S. load, which is quite different

TABLE OF LOAD CHARACTERISTICS FOR DIFFERENT LOAD DIAGRAMS, ALL GIVING 25 PER CENT LOAD FACTOR.*

(See Load Diagrams in the Figure.)

No. of curve	Description of load	Mean square factor	R.M.S. or form factor multiplier for 100 per cent load factor copper costs	Load factor of losses	Voltage-drop at top load and per cent of plant to meet them. Delivery volts assumed constant	Generating capacity for top-load losses †	Daily loss †
				per cent	per cent	kW	units
1	{ 12 hours 0 to 4 times average load .. / 12 hours 0 load .. .. }	$2\cdot\dot{6}\dot{6}$	1·63	16·6	12·25	245	978
2	{ 9·6 hours 0·25 to 4 times average load / 14·4 hours 0·25 average load .. .. }	2·313	1·521	14·5	13·2	263	913
3	{ 8 hours 0·4 to 4 times average load .. / 16 hours 0·4 average load .. .. }	2·084	1·44	12·95	13·9	278	864
4	{ 6·857 hours 0·5 to 4 times average load / 17·143 hours 0·5 average load .. .. }	1·917	1·384	11·97	14·5	289	830
5	{ 5·647 hours 0·6 to 4 times average load / 18·353 hours 0·6 average load .. .. }	1·67	1·292	10·41	15·5	310	775
6	{ 3 hours 0·8 to 4 times average load .. / 21 hours 0·8 average load .. .. }	1·386	1·177	8·65	17·0	340	706
7	{ 1·548 hours 0·9 to 4 times average load / 22·452 hours 0·9 average load .. .. }	1·197	1·094	7·47	18·3	366	656
8	{ 6 hours 4 times average load .. .. / 18 hours 0 load .. .. }	4·0	2·0	25·0	10·0	200	1 200

* The table shows that as the copper section is diminished in relation to the maximum load, with falling form factor, so as to keep copper capital charges and losses costs equal, the voltage-drop and capacity to meet it at top load increase. The simple Kelvin relation upon which the table is worked assumes that all units lost have a uniform value. They clearly have not, as their cost must increase as the load factor of the losses decreases—or as the plant capacity needed to keep up the voltage increases. In any actual case this effect is diminished if there is a diversity factor among the feeders. The simplest form of correction to the simple Kelvin expression is to take a higher cost for the lost units. If boosting is needed, the lost units must be given the proper higher value including capital charges, etc., on the booster, or its equivalent.

† These columns give the comparative daily losses for a daily delivery of 12 000 units in every case, based upon those for 100 per cent load factor, i.e. for a steady load of 500 kW delivered, and the additional plant required at the peak load to keep the delivery voltage constant.

For the 100 per cent load factor the losses are taken as 5 per cent of the units delivered, or 600 units per day: the plant capacity 525 kW. For the 25 per cent load factor the peak load is 2 000 kW delivered, and the plant capacity at the peak 2 000 kW, plus the amount given under the heading "Generating capacity for top-load losses."

section, from the "Kelvin current density" calculated for 100 per cent load factor.

To show how form factor varies with the load diagram for the same load factor, say 25 per cent, let the load diagram be triangular, rising from zero at a uniform slope to four times the average load, and falling again at a uniform slope to zero. The time base of the triangle will be half the duration of the period, say 12 hours per 24 hours. The mean square value will then be $2\cdot\dot{6}\dot{6}$ times the average over the 24 hours, and the form factor $\sqrt{(2\cdot\dot{6}\dot{6})} = 1\cdot63$, instead of the values 4 and 2 for the rectangular load diagram. (From the from the relation between the capital and running charges of the generating plant for various load factors.

For any but the rectangular load diagram the load factor at the delivery end of a feeder is higher than the load factor at the station end, because the load factor of the losses is lower than that of the useful load. Also the maximum losses are an addition to the peak load and add to the station capital chargeable against the units sold through the feeder. The total or combined peak load of distribution losses takes up part of the station capacity and diminishes the paying load which can be supplied from the station. This loss of plant

capacity is allocated to particular feeders in proportion to their individual peak loads, and inversely as the diversity factor among them, or the maximum load of each divided by the diversity factor.

The diagrams and table on pages 852 and 853 illustrate these points. The load factor is 25 per cent in all cases, but results from different load diagrams, these being of simpler form than are usual in practice, for ease of calculation. The last two columns of the table are of actual kW and unit values for the following assumed conditions: That the load diagram is for 24 hours; that the feeders are of equal length and each delivers 12 000 units in the time; and that the "Kelvin current density" for 100 per cent load factor (a steady 24-hour load of 500 kW delivered) gives a drop of 5 per cent of the delivery pressure, representing copper losses of 600 units per day. The other columns give relative figures.

One could go on to show how the capital charges and running costs of transformers, converters, switchgear substations and the like vary with the load factor and the shape of the load diagram. It must suffice to say that in every case there is a large proportion of the total annual charges which is fixed by the maximum demand upon each item, and is consequently shown in the cost per unit as inversely proportional to the load factor; also that this proportion is individual to each section of a distributing layout, so that there is no compensation for a badly-loaded section by the existence of better-loaded sections. It is only the feeders, substations, etc., feeding a number of distributing sections that get the benefit of diversity factor. Generally the copper sections of the ultimate distributors to which consumers' services are connected have to be determined by voltage variation rather than by economy; hence the capital charges will depend upon the maximum loads (strictly, the integrated product of loads and distances at the peak loads) and the distances between the feeding points and the most remote services. The losses will still be those corresponding to the R.M.S. loads.

Enough has been said to show that the relations between costs per unit sold, load factor and form factor, are not alike for generation and distribution; the latter are more complex, and more affected by the load characteristics.

Distribution losses ("units unaccounted for") are paid for in the generation costs. Generation costs "per unit sold" include these distribution costs, a fact not always recognized, which makes the comparison of station costs upon the "units sold" basis quite misleading where the distributing conditions are not equal.

Cost per unit sent out is the only fair basis for determining station economy; the commercial efficiency of a station has no definite meaning where sales are effected through a distributing system which puts its lost units to the debit of the station.

The value of the distribution losses per unit increases at each link in the chain between the station busbars and the consumers' terminals. The units delivered by a feeder cost more than those delivered to it, by the sum of the losses and the capital charges on the feeder. The units delivered by converting plant to direct-current distributors cost considerably more than the units taken from the alternating-current feeder, by the sum of the losses, capital charges, and attendance costs of the converting substation. The cost of the losses in the distributors is the cost of the units delivered to them, which is greater than the cost per unit sent out from the station. This greater cost should be used in calculating economical copper sections for each stage. Most costly of all are the units lost by defective meter registration. Their value is their selling price, for they are consumed and not paid for.

For the reduction of distribution costs a much larger use of measurement is necessary. It is impossible to control distribution losses, with due regard to economy of capital, unless one knows their magnitude at each stage. Reduction seems necessary, when it is realized that there are systems where the units sold are about 55 to 60 per cent of the units sent out.

This disquisition on distribution costs is entirely pertinent to the question of tariffs for domestic supply, first, because the total of distribution costs, capital charges and losses is a serious element in the total cost of supply, and secondly because load characteristics affect these costs more, and not in the same way as they affect generation costs.

This can be shown by considering how the costs per unit sold are made up. Start from the consumer's terminals. To give a supply capital has been spent by the undertaker upon the service cables, meter, supply fuses, laying, jointing and fixing. This is individual to the consumer, and on that capital the consumer should pay a certain annual percentage. The outlay, on the average length of service, can be represented by some minimum cost, plus an amount roughly proportional to the declared or connected load. This item of the charge might be included in a connected-load charge, which should go by steps and would be appropriately included in a "meter rental" charge. If it is distributed over the charge per unit, evidently it should vary inversely as the individual consumers' load factors, which is equivalent to making it an element of a kW charge in a two-rate tariff of the usual kind. But the kW figure for this item of charge should be the number of kilowatts of declared or connected load, not the estimated or observed maximum demand.

The next step is the distributing main to which the service is connected. It will generally serve a number of consumers. How is the annual cost of it to be allocated between them?

Any distributor with any load distribution along it can be reduced to an equivalent main of the mean length, supplying a load at its end which is the equivalent in magnitude, units delivered in a given period, and load diagram, to the aggregate loads of all the consumers served. The maximum load is the sum of the individual consumers' maxima divided by the diversity factor among them; and the load factor of the distributor is the ratio of the total units delivered, to the product of that combined maximum and the hours covered by the period.

The capital cost taken must evidently be that of the actual distributor; for though the equivalent main should have the same copper cost, it will generally be

shorter, and the cost of laying depends upon the length and other circumstances. The copper cost and the losses will be determined by the permissible voltage variation between the feeding point and the most distant services.

The same process should be followed back through feeders to distributors, substations, feeders to substations, etc., which will give as a result the total cost per unit delivered at any particular feeding point, including the capital charges and the cost of the losses. At each converging point of different loads, the benefit of the diversity factor between the constituents is taken into account, and the costs of labour, etc., added.

Evidently the cost of the units sold through the particular ultimate distributor in the course of a year is made up of:

(*a*) The cost of the greater number of units delivered to the distributor, including all the capital charges and the cost of the losses up to the feeding point.

(*b*) The capital charges on the distributor.

(*c*) The capital charges on the services, meters, etc., and the cost of meter-reading, etc., for all the consumers.

It has already been suggested that (*c*) should be charged to the individual consumers as a meter rental, or it may be as a charge per kilowatt of connected load.

The total of (*a*) and (*b*) divided by the total units sold gives a sum per unit, which with a reasonable addition for profit—unless profit is included in the capital charges at each step, which is the sounder way—is a proper average price for all the consumers.

This is a "flat rate," which, however, includes a kW charge based upon the aggregate load factor, an average charge per kilowatt of the individual consumers' maximum demand divided by the diversity factor among them. It is really treating the whole of the consumers on that distributor as a single consumer, and charging that consumer a maximum demand rate, plus a unit rate. This would be quite equitable if all the consumers had similar load characteristics; but if some have large peaks at the time of aggregate peak load, and low load factors, and some have more favourable loads, the good would be paying for the less good and would have some reason to complain. Also, the price would be higher than necessary for the good, and too low for the less good.

Such a calculation does, however, permit of the determination of flat rates for hypothetical groups of consumers with similar load characteristics, and an assumed load density (kilowatts per unit length) along a distributor. The resulting flat rates will be minima for each class of consumer investigated, which must be loaded to meet the fact that consumers will not usually be in groups of homogeneous load characteristics.

The practical application of the method which the author suggests for arriving at tariffs for domestic supply is, first, to classify consumers by their load and diversity factors. The best basis for this is observation of selected groups with similar proportions of connected load for different uses. Something of this kind has already been published, for example in Mr. Gillott's paper on "Domestic Load Building," * and very likely more has been done but not published.

* *Journal I.E.E.*, 1923, vol. 61, p. 197.

Mr. Gillott's paper showed that in a homogeneous group of consumers using cooking apparatus the diversity factor was about 9, so that the kW charge to them would be properly one-ninth of the individual maxima. He also showed that this charge would be fairly well represented by charging the lighting rate for their lighting consumption, and a much lower rate for the rest.

There are many tariffs in use based upon the same idea—"telephone," rateable value, floor area, quarterly charges per lamp of unit wattage installed, and others—all endeavouring to fix a basis which represents a kW charge. Very generally the underlying notion is that lighting is the measure of the peak load to be charged for on the kW rate for domestic supplies. This notion may be generally correct at present, but the author suggests that the domestic lighting load will become of diminishing importance as "other uses" become generalized. Many of the two-part domestic tariffs referred to above are difficult to justify on any logical ground; and smaller householders are repelled by an obligation to make relatively large fixed periodic payments. Tariffs which permit the use of prepayment meters are indispensable to the generalization of domestic electrification.

As there will be for a long time to come—perhaps always—considerable differences between the load characteristics of domestic consumers living in the same districts, it will not be correct to use the minimum rates worked out on the hypothesis of homogeneous groups on each distributor. The actual rates will have to be higher than these minima, because each class, scattered over the supply area and mixed up, will not be the equivalent of a single consumer.

The practical method of classification can be worked out only for each supply area, because local habits and customs, prevailing industries, etc., will have their effects on the load characteristics. The general method, the author suggests, should be to ascertain the load characteristics of consumers with various proportions of lighting, cooking, heating, motor, etc., appliances, and from these observations define the classes and fix the rates.

Some things must be averaged. It is not practicable or legal to make differential charges depending upon the distance of consumers from the generating or bulk-supply source, so that an average distance and cost must be taken. There is the legal prohibition of "preference" to be observed; hence different flat rates must be based upon defensible differences in circumstances.

For the immediate future it may be advisable to limit the maximum lighting demands of domestic consumers under these tariffs. There are various forms of limiter available. Generally, in small houses the lighting circuit is bound to be separate from the cooking, heating, etc., circuits, so that the use of current limiters is feasible. One rather attractive proposition is to connect the lighting to the circuit supplying a heat-storage tank, with a limiting switch to turn off the heater as soon as more than one or two lamps are in use. This would make the lighting part of a load with 100 per cent load factor. Current limiters and

the like cannot be discussed here, but a condenser in the lighting circuit on alternating-current distribution has attractions.

The object of this paper is to show :—

(1) That the present heavy ratio of distribution to generation costs can be materially improved by improving the distribution load factor, especially by improving it all over any supply area.

(2) That it is necessary to keep control of distribution economy by measurement, and to apply the known principles of economic design to distribution networks.

(3) That tariffs recognizing load factor and diversity factors of domestic consumers by classes are practicable and will attract the most desirable domestic load, thereby improving the utilization of distribution systems and permitting progressive reduction in supply charges.

Discussion before The Institution, 2 April, 1925.

Lieut.-Col. W. A. Vignoles : Surely all the electric supply undertakings in this country must by this time have realized the necessity for developing the domestic load, and have already provided some sort of tariff to encourage it. If that is so, why are we once more discussing this question of tariffs ? Having come to the conclusion that this discussion was not required, I examined some statistics which had been given me, to see whether my contention was justified. I find that out of 260 towns, 144 are using multi-part tariffs, and as regards other activities 117 are hiring out apparatus, and 109 have showrooms. The figure 144 is somewhere about 50 per cent of the total, and this seems to show that I am wrong and that there is still need to discuss this question of tariffs. What is actually required, however, is more internal propaganda to convince the supply undertakings that it is time they pushed the sale of electricity for purposes other than lighting and adopted one of the tariffs which can be explained to the consumer in an easy manner.

Mr. Sayers's system is essentially a series of flat rates, but surely this will be impossible to work. A consumer has electricity for lighting purposes, and he begins to use it for some other purpose. As he does so he will go from one class to another class, and will never be able to tell which class he is in, and the man who is trying to sell him electricity will not be able to tell him. Tariffs cannot be devised scientifically to provide a revenue exactly in agreement with the cost of supplying a particular consumer; it is only possible to get a rough approximation.

Messrs. Wilkinson and McCourt have gone back to the complicated system of Mr. Wright, of so many units at a high figure and so many units at a low figure. Because no one could ever make the consumer understand how many units he ought to have at the high figure and how many at the low figure, the system was given up. The present authors complicate it still more by giving the consumer so many units at 8d., so many at ½d., and then switching him back to a third rate of 6d. Further, this necessitates a special piece of apparatus which supply undertakings cannot afford if they are going to sell electricity on commercial lines. There are thousands of consumers in each town, and it would be impossible to substitute this special meter for all the existing ones. We must have a tariff by means of which a consumer can be charged according to the reading of a single meter. A more serious objection to the authors' system is that it is based on the consumer's maximum demand for all purposes. The consumer is therefore not getting the benefit of the diversity factor between one consumer and another.

The more I study these two papers the more I come to the conclusion that the only practical tariff is a straightforward two-part tariff. It must be such a tariff that the salesman can go to the consumer and say "Your first charge is so much per annum; in addition to that you will be required to pay so much a unit for the energy which is metered." The running charge should be the lowest possible figure—1d., ¾d. or ½d., if it is possible to get down to that—but it certainly should not be more than 1d. I am quite certain that this is the system which will eventually be used—a fixed first charge and a low running charge. This has been proved in many towns to be a good selling tariff. The consumer understands it, and thousands of consumers are already on it. The Electricity Commissioners are anxious about tariffs which can be made compulsory without giving the consumer the option of going on to a flat rate. Whilst a rateable value tariff is quite satisfactory in some towns—it is in mine—it cannot be said that 18 per cent on the rateable value in one town is the same as 18 per cent on the rateable value in another town. All that one can say is that 18 per cent on the rateable value in such and such a town produces an amount of money which covers the standing charges, and perhaps 20 per cent would be required in another town to cover them. I quite admit that it is difficult for a Government Department to have to make such a tariff compulsory, but this difficulty will no doubt be overcome by the Committee which I understand is being formed. I think they will find some method of fixing this first charge; I should like to say, however, that whilst the Grimsby undertaking was the first to get powers to enforce such a tariff, we have not enforced it. We rely on a high flat rate to encourage people to come on to the rateable value system, and we shall only ask the Commissioners to approve a compulsory tariff in special cases, or in cases where we go out into the rural districts, where it means possibly a large capital expenditure for each consumer. I do not think, however, that we shall ask for any such special tariff for the town supply.

I maintain that this tariff problem is settled, and that the sooner we get on with the selling of electricity on a two-part tariff the better it will be for the industry. I believe that a good deal of this discussion on tariffs has arisen from the fact that many engineers in supply undertakings think that they can sell electricity by devising a tariff. I hold that that is entirely wrong; it is impossible to sell electricity by a tariff only. I am quite sure that all the engineers of the big, successful undertakings are of the opinion that the only way to sell electricity is to do so by means

of salesmen, the tariff being a part only of his equipment.

Captain J. M. Donaldson: Flat rates have proved in the past to be exceedingly unfair either to the consumer or to the supplier, and it is very difficult to see how they can be otherwise than unfair. Mr. Sayers's plan of selecting and grading his consumers raises another very practical difficulty—that some individual will have to make the selection, and this will be a thankless job. The maximum-demand system, which has been spoken of rather scathingly by Col. Vignoles, but which, after all, is the basis of all the tariffs we use, is useless for direct application to a domestic load. One cannot, with any commercial hope of success, apply any tariff depending on the demand which a heater or cooker may put on the mains at any time, as it is impossible to specify what that time will be. The demand is relatively so large in comparison with the lighting demand that no single tariff will fit both.

I found the results given in Messrs. Wilkinson and McCourt's paper rather difficult to understand, because it seems to me that unless the device is applied only to the lighting circuit, and unless the lighting circuit is kept absolutely distinct from the power circuit (which, of course, is a mistake, in some cases at any rate), a consumer is bound to get on to what I may call the "penal rate" every time a cooker or heater is used. The fixed charge of 8d. must be based naturally on the demand for lighting, and quite properly of course; but as soon as ever a heater or cooker is put on it is bound to switch the meter on to the "penal rate" and, so far as I can see, the consumer will find a difficulty in getting off it. Some figures which I took out showed that in an ordinary case the price per unit on the first scale would probably be about 3½d. for heating or cooking. On page 849 the authors suggest that the unfortunate consumer is going to be asked to install storage batteries on his premises to take the load at odd times and charge up. Whilst this would no doubt be welcomed by the supply undertaking, I think that the experience gained by people since the introduction of broadcasting has not rendered the storage battery very popular. It really comes to this, I think—that it is necessary to have a two-part tariff with a fixed rate, and a low rate at which current can be obtained for any purpose. It is quite true that it is not desirable that the heaters which are installed nowadays should be connected to the lighting circuit; it would hardly be practicable. At the same time there is a great deal of other apparatus, such as irons and toasters, and even bowl fires, which can very conveniently and cheaply be put on to the lighting circuit. Therefore any tariff which entails separate power and lighting circuits is really a backward step. As far as the fixed part of the tariff is concerned, it will really be based on the maximum demand for lighting, and if this can be arrived at in a convenient manner it is better to do so, because the rateable value is only arbitrary, and floor space equally so, people having different ideas of how they propose to light their homes. My preference is for a system in which the fixed charge is based on the lighting demand, or rather on a fixed proportion of the lighting wattage installed. My experience is that such a system works very well, except in those cases where a large number of decorative lights are used. Such cases can, however, always be dealt with by making a test which indicates exactly what the demand is normally at any one time, and basing the tariff on that figure. It appears to me to be quite useless to attempt to base a demand charge on the heating and cooking load, because no one knows how it will work in practice; and unless an undertaker can tell a consumer that it will only cost so much per hour to run, say, a heater, I am afraid that the consumer will look upon him with suspicion. If there is a flat rate, however, and a fixed charge depending only upon the lighting, then of course it is possible to say definitely what it will cost to run the heater for an hour.

Mr. J. R. Blaikie: Mr. Sayers states that the cost of mains is from two to four times the cost of generation, but I think that that figure calls for some substantiation. Col. Vignoles seems to think that electricity cannot be sold by means of tariffs, but in my opinion the whole history of electrical development has shown the immense value of tariffs. Dr. Hopkinson set out to reduce the cost of electricity below that of gas, and he did so entirely by what is known as the two-part tariff. If we had not had the advantage of Dr. Hopkinson's work we should be in an entirely different position to-day. One of the failings of the majority of papers written on the subject of tariffs is that they do not show how these various stand-by or first costs are arrived at. It is generally taken for granted that they consist of a certain cost and a certain running cost. It is very important to arrange these two factors suitably, and we have continually to split up the segregation of consumers to do so. If we take the original Hopkinson principle we have a number of assumptions. One is, for instance, that the consumers are all at an equal distance from the point of generation. That, of course, is a very great assumption, and the cost of supplying a consumer at a long distance is very much greater than the cost of supplying a consumer at a short distance. It might be possible to devise some system of tariffs which would take the distance into account and possibly average the kilowatt demand. Such a system might be worked out on the rate per yard by taking simply the length of a consumer's frontage. We cannot, however, take the distance of the consumer from the station; but every consumer is slightly further from the station by reason of the other consumers' frontages. If every house in a street were connected to the electric main, the sum of the frontages would represent the total length of the main. By dividing the total cost of the mains by the total frontages the price could be fixed. This method could also take into account the Hopkinson principle, from the point of view of mains, by apportioning the standing charges per yard of main to keep it up to pressure. It would be quite possible to work out a tariff which would be as successful as that based on the rateable value, or floor area simply on the frontage of the house or premises, and possibly, as Mr. Sayers points out, it might be based on the square of the frontage. The coal consumption in a Parsons line shows that somewhere about 10 per cent of the total coal is used as a standing charge. That is a very essential point. There are a

great many engineers in the country who believe that the stand-by charge in coal is simply that required for banking the boilers and that it is not the belt that occurs under the straight line that cuts the axis of the coal scale. It is a very important point, because it makes it possible to add a great deal to the standing charge, as Dr. Hopkinson showed. With regard to equity in tariffs, we must have something to show if challenged by a Government Department or if any given tariff is to be made compulsory. The tariff must have some approximation to equity, but, as Col. Vignoles and other speakers have remarked, it is far better to leave the consumers alone. The maximum-demand system did extremely useful work in the collection of data, but it is impossible to make people understand it and sympathize with it. I think we may say that points of equity as between consumers are not practicable, and we must regard equity only in forming the general scheme for the benefit of the authorities who may criticize it.

Mr. E. W. Cowan: Referring to the paper by Messrs. Wilkinson and McCourt, on page 847 the authors say that the consumer will use every means not to exceed his agreed demand, and on page 849 they refer to the strong incentive to the consumer to decrease his demand on the station. Are the authors quite certain that they would gain an advantage by preventing these excess units being used and paid for by the consumer? If he will still use the same number of units, and use them within his maximum demand, then the advantage is quite obvious; but will he do so? When there is full load on a plant or main, the excess units taken by consumers would be unprofitable to the supply station. The situation seems to call for a means of preventing these units being consumed when the system is fully loaded, and only then. If this view is correct, the question arises as to whether the authors' device can be modified to produce that result. If the device were fitted with a potential coil instead of a series current coil, and adjusted so that the change-over took place at a critical predetermined pressure, which pressure for the particular locality of the consumer would represent full load on the supply mains, then the supply undertaking would be fully protected. That device is not, however, practicable because the consumer whose neighbour is taking an excess demand would be charged at a higher rate than his neighbour, and this might give rise to unpleasantness. If, however, the device could be modified so that without undue complication the series current coil could be put out of action whenever the pressure was above a certain predetermined point, it would solve the difficulty. Quite apart from the economic or practical merits of this suggestion, I am afraid that the authors of both papers would regard it as involving a violation of the principle which they lay down as being the only right principle. I do not agree, however, that the principle laid down is correct. I think that it is scientifically and economically incorrect, and also inequitable. The idea that equal treatment connotes equitable treatment is, I think, fallacious. The authors are mistaken when they attribute to the late Dr. John Hopkinson the principle that the price of electricity to each consumer should be based upon the cost of supplying him, including his proportionate share of standing charges. It was Arthur Wright who enunciated this principle. Dr. Hopkinson's paper dealt with one commodity only, namely, the service of light, and the author said: "The charge for a service should bear some relation to the cost of rendering it." Later in his paper he speaks of a rate having "some sort of relation" to the cost of supply. He was quite alive to the practice of what economists call discriminating between prices, that is the adaptation of prices to market conditions, and he gave in that paper an instance of it, quoting the Post Office as charging ½d. for a circular and 1d. for a letter, whereas the carrying of both cost exactly the same. Dr. Hopkinson was calling attention in that paper to the importance, which is agreed to by everybody, of studying the proper influence of cost upon price, but I cannot find that he advocated that the influence of the value of service should be ruled out. It has always seemed strange to me that no contribution, as far as I know, has been made by any electrical supply engineer which does any sort of justice to the view that both factors should be recognized and allowed for in prices. A leading article in the *Electrical World* to which I referred to-day contained the words: "In order to stimulate demand at varying hours and in various quantities, the rates for electrical service should be based upon other conditions than the cost of service alone. The value of service, together with other conditions, should be taken into careful consideration when rates are made for different classes of consumers," and so on. There is a very large body of people who agree with that view. Such men, I think, form the great majority amongst those who are responsible for the administration of a public utility. All the railways of the world base their rates upon the influence of both factors, and so do all shipping lines. I would beg the authors of the papers to dismiss from their minds that there is any inequity in paying regard to the value of service, that there is any penalizing or subsidizing process accompanying its consideration, or that there is any theoretical unsoundness in it. It seems to be a pity that in our great industry a serious point of view, widely held and adopted in public service, should be treated with inattention and disregard.

Mr. J. W. Beauchamp: The two-rate meter proposed by Messrs. Wilkinson and McCourt does not appear to find favour with previous speakers, but I think that this is because the discussion has centred round domestic supply. Vast as that field is, there are a great many other supplies, and I think that the invention will be useful for certain of them. I do not know whether it will be of service for the household because I believe very strongly that we must sell electricity on the simple multi-part tariff. We can only make such a tariff a success by maintaining high alternative flat rates. A good deal of attention has already been given to whether these multi-part tariffs should be made compulsory or not; the general feeling has been that they should not be, and therefore they need the support of a fairly high flat rate and good salesmanship. Those who are selling electricity for lighting at extremely low rates are doing almost as much harm to the development of this industry as those are who are selling it at extremely high rates. It

makes it quite impossible in the district to push multi-part tariffs, and it generally means the frittering away of valuable surpluses which could be spent on development work.

Mr. Sayers particularly refers to cost. I feel that when we touch this great domestic load, that is to say, when we are dealing with thousands of small premises, we cannot talk about the cost of supplying the individual consumer, because there is no such thing; it varies from moment to moment or from day to day with the other consumers. The tariffs for big consumers are based on the cost of power. This, however, is not done by law, but by competition; it is the only way to compete with gas or coal or private plants. I am in full agreement with Mr. Cowan's statement about the value of the service; it is a perfectly good way in which to sell anything, and I see nothing in the law which prevents it. The law only asks that we should be reasonable as between those in somewhat similar conditions. We are very apt, in making a tariff, to lose sight of this. No difficulty arises when we sell electricity for lighting and power, but when we begin to apply electricity in a large way for heating and cooking we are faced with the fact that the physical yield of 1 kWh of energy to any individual may be so different. A unit gives him a certain amount of light which is very cheap to him at 6d. It gives him 1 h.p.-hour for his motor, which he may be very pleased with at 2d.; but when he wants to cook a dinner he finds that 3 units are required, and the unit may have to be sold at 1d. in order to compete with gas. This seems to me to point to the fact that we must have multi-part tariffs for a long time to come. If one wishes to sell all units at the same rate one must also have some kind of rental or fixed charge. None of the present methods of assessing this fixed charge are, however, free from objection, and it remains to choose the best method and adhere to it.

I do feel there is a field for such a device as that of Messrs. Wilkinson and McCourt, and I also feel that analytical papers like that of Mr. Sayers are valuable. We do not want to get too unscientific. We want to feel that we have behind us the theories of Hopkinson and other investigators; but in order to sell electricity we must have the very simplest tariff. We can offer light and power at a medium price, but we must have competitive rates for heating, and I maintain that we can generally afford to give those rates if only we get sufficient business.

Mr. R. O. Kapp: I think that the line of investigation which Mr. Sayers has taken is of the greatest importance to the supply engineer. I do not think we should underrate the importance of finding out exactly what an individual consumer costs us. But when we have done that, what is the moral we are to draw from the facts and figures we have elucidated? It seems to me that though it is necessary to know what each consumer costs we need not always adjust our tariff accordingly. The purpose of a tariff is not to dole out justice all round, but to do business; I would say to do business with at least a small profit attached to it, and if one devises a tariff to meet those conditions one has really done the best for everybody. The two-part tariff is necessary for those large power consumers whose supply involves a large turnover with a small profit. The charge must be at the rock-bottom price the supply undertaking can afford, and a flat rate at such a price to a large consumer with a lower load factor than had been allowed for might land the supply undertaking in the bankruptcy court. That is really a justification for a two-part tariff. I can never understand, however, in the case of the domestic consumer, whose rate, after all, covers so large a margin for contribution to the overhead charges, what gain there is in a two-part tariff, or in any method for limiting what he buys. So long as his charge is so arranged that at any load factor he is paying not only the net rock-bottom cost but also some sort of contribution to the overhead charges, he is a desirable consumer. Therefore it seems to me that the flat rate which will be low enough to guarantee this condition at the lowest load factor likely to occur will meet the case best.

Mr. F. W. Purse: My objection to the meter proposed by Messrs. Wilkinson and McCourt is that it will switch over from the low rate to the high rate at any time. If, however, the Brockie-Pell patent, by means of which very high-frequency current can be superimposed on the ordinary supply, were to be adopted, it would be possible to switch the meter over from the low rate to the high rate when required. This could be done during the peak, after which the meter could be switched back on to the low rate. With regard to Col. Vignoles's suggestion that we should have no more papers on tariffs, I am never one to say I know everything, and I should like a repetition of papers on tariffs if only to give us the opportunity of examining the question afresh. I do not think there will be any disadvantage two or three years from now to hear someone else's ideas after studying the matter from another angle.

I think that Mr. Sayers has done well to call attention (on page 851) to the four different classes of consumers. Later in the paper he refers to the cost per unit sent out as being the only fair basis for economy. I have for many years always taken my comparison of costs at the station on the cost of units sent out or of the units delivered to the feeders. On page 855 he says: "Many of the two-part tariffs are difficult to justify on any logical ground." He includes in those various tariffs a kilowatt rate, yet on page 854 he says: "But the kW figure for this item of charge should be the number of kilowatts of declared or connected load, not the estimated or observed maximum demand." These two statements appear to be contradictory. At the bottom of page 855 he says: "The practical application of the method which the author suggests for arriving at tariffs for domestic supply is, first, to classify consumers by their load and diversity factors." This, however, would be very difficult to do, and would give rise to a great deal of trouble. The multi-part tariff is undoubtedly the ideal tariff, but I agree with Capt. Donaldson that the best in order of fairness is the installed capacity, that is per 50-watt lamp. My principal difficulty is the initial cost of the installation to the consumer. I am trying to get powers so that when a prospective consumer, no matter whose house it is,

wants an installation I can supply it, and I wish to be empowered to enforce the charge for the installation in that house so long as electricity is used, irrespective of whether the original tenant is in residence at the time or not. As things are at present, if we put in an installation for a consumer on hire terms and he leaves, the next tenant may say: "I did not make the bargain. I am not going to pay you," and as we have no power to enforce the charge we have to remove the installation. I think that the two-part tariff based upon the size of the installation is proceeding on the right lines, and that it is very necessary for the development of the domestic supply.

Mr. F. Gill: It is sometimes possible to obtain useful information from another business. I cannot throw any light on this subject from the lighting point of view, but I think that I can say something of interest from the telephone point of view. The consensus of opinion in regard to telephone costs is that analysis of costs is very necessary and very desirable, but that such analysis of costs does not determine the tariff. The way in which it is done in the telephone business nowadays is somewhat as follows. The load is studied and the way in which it varies is discovered. (Remember that the telephone business has just as many kinds of consumers as the electric supply business, if not more.) Having done that, many schedules of rates are drawn up; in some cases 8, 12 or 15 schedules are prepared. These must be checked against the total installation in order to discover whether they will produce the money required to run the business properly. Those different schedules are then analysed and criticized in quite a number of different ways. They must be simple, the public must be able to understand them, and they must be harmonious in themselves. They must be attractive to the public, otherwise they will not serve their purpose. They must encourage business, and they must be reasonable. At this stage of the examination a number of the tentative schedules have been discarded, and one or more remain which satisfy all those other points which have been raised in the discussion—for instance, what the traffic will bear and how the public will regard the tariff—and one can be chosen which will enable the business to grow.

Mr. P. Rosling: I wish to speak from the point of view of a consumer. I agree with a previous speaker that it is very desirable to have the lighting and heating on separate circuits. Over many years' experience I have not experienced much trouble owing to the lighting fuse going, but my heating fuse has blown on a number of occasions, so that if the lighting and heating circuits were on the same fuse I am afraid the average person would find himself too often in difficulty. I suppose that, with two circuits two meters would be necessary, and this would increase the connecting-up cost, but perhaps that could be overcome in some other way. Many years ago I went into the question of the relative value of gas lighting and electric lighting and, after taking out very carefully my costs over 9 years for running a small plant of my own, including depreciation, I came to the conclusion that electricity had cost me about 7s. a unit. My brother-in-law, who started housekeeping about the same time as I did, had gas in his house, and over 9 years his bills for gas and keeping his house clean were within 1 or 2 per cent of what I paid for the same purpose, and he paid 3s. 6d. per 1 000 cub. ft. for gas. I say therefore that the equivalent value was 3s. 6d. for gas and 7s. per unit for electricity, using fish-tail gas burners and 4-watt-per-candle-power electric lamps. I have always wondered why such a low price is charged for electricity for lighting, because there is such an extraordinary margin in comparison with other systems of lighting private houses. It might actually have been better for the industry if higher prices had been charged, and more energy put into the obtaining of customers.

Messrs. G. Wilkinson and R. McCourt (*in reply*): The discussion has shown conclusively that in the minds of electrical engineers there is no certitude that the best tariff for selling electricity has yet been devised. No attempt has been made to disprove or controvert the statement that a two-part tariff is the most successful in encouraging an increased use of the supply, and that the first part of the tariff—the fixed charge—should be based on the electrical demands of the consumer, instead of upon rateable value, floor area, and other irrelevant bases at present in use. To assume that a consumer's lighting requirements only should be taken as his maximum demand is an idea which should be abandoned; the time is rapidly approaching—if not already here in many places—when the lighting demand and output will be only a small proportion of the total demand and output. To allow the daily peak load to dominate the consideration of tariff problems so much as it has done leads to unsound conclusions; rather we should visualize and prepare for the time when the load factor of the station will be such as will make the peak substantially less important relatively to the total output. Supply undertakings are too ready to tell consumers at what hour of the day they should take a supply. The general public want to use electricity just when it suits them, as they do any other daily necessity, and a tariff which lends itself to this end, without the intervention of expensive time clocks and complicated book-keeping, is the one that will ultimately prevail and displace present-day complications and unjust tariffs. These characteristics we claim for the uniform tariff.

Before summing up we will deal with some of the specific objections levelled against the system during the discussion.

Colonel Vignoles states that discussion on tariffs is not required, but he withdraws this statement later as a result of his more detailed investigations. Surely, the fact of the Government appointing a Committee to consider and report on the question of tariffs is conclusive evidence that the standardization of tariffs is a prime factor in future development; therefore any paper or discussion by electrical engineers that assists this object is both desirable and beneficial. The Wright system is characterized as a complicated system, but its equity is not challenged. True it is difficult to explain to the layman, but the uniform tariff meter which we advocate renders this explanation unnecessary and the consumer knows in advance exactly what number of units he has to pay for at the initial high figure to cover standing charges; he also knows that

the units consumed beyond this figure are secured at such a cheap rate that he can afford to use electricity for all purposes and realize all the convenience and advantages it is capable of conferring. As stated in the paper, the consumer is not switched into the third rate except when he deliberately decides to do so for reasons of his own; and although this third rate is put as high as 6d., in actual practice 3d. or 4d. per unit would probably be the maximum price. The claim that "we must have a tariff by means of which a consumer can be charged according to the readings of a single meter" is precisely what we are proposing, namely, a meter of extremely simple and reliable construction without time clock or other contraptions so often used in connection with two-part tariffs to-day, which place undue restrictions upon the consumer and incur heavy supervision, repair and maintenance charges on the supply undertaking. We are credited with the intention of putting existing consumers on the uniform tariff, scrapping their old meters and imposing upon them additional expense for uniform-tariff meters. We have made no such suggestion and disclaim any such intention; it is in the new areas and to new consumers that the modern meters and methods would be offered as an alternative to existing tariffs. Old customers would come in by degrees when the new meters and tariff demonstrate their economy and superiority, as they would do in a comparatively short time. This will ensue without special effort on the part of the salesman, a few favourable comparative results being much more effective in business-getting than the special pleading of plausible salesmen. Colonel Vignoles is content to depend for increase of business upon expert canvassers advocating possibly inequitable tariffs; we prefer an equitable tariff which, while holding existing business, is attractive enough to secure the additional business which present tariffs do not attract.

Captain Donaldson's criticisms are generally fair, having in mind "the state of the art" as it is commonly known to-day. The full significance and value of uniform tariffs will not be realized until simple means are provided enabling consumers to take electrical energy during periods when at present there is negligible demand; in other words, until the load factor is greatly increased in each individual case. It is recognized that in an all-electric house the number of units consumed will be many times that in a house equipped for lighting, the usual electric iron, vacuum cleaner, an electric radiator or two for occasional use and, say, a breakfast cooker. The all-electric house calls for electric heating all day long for at least eight months in the year, the amount varying according to the weather; it demands supply for cooking every day and a generous supply for water-heating purposes. This all-electric demand means an increased consumption per house, of 5 to 10 times the present-day average. With present-day methods this supply is not commercially attainable. Fortunately, however, the major portion of the demand, is for the production of "low grade" heat, viz., say, half the cooking and all water and room heating. Low-grade heat can be efficiently and cheaply stored, and for this purpose the consumer can take electricity during hours when there is at present none or very little electricity being used. Herein lies the possibility of attaining a 50–75 per cent load factor in place of the present average of 22–25 per cent. Careful investigations reveal the fact that the second 25 per cent increase in the load factor, viz. from 25 per cent to 50 per cent, can be generated and delivered to consumers on existing mains at about one-sixth the price per unit of the first 25 per cent and sold with profit at about one-quarter the average cost. To describe this method in detail is outside the scope of this discussion, but in the near future such off-peak storage radiators, water heaters and cookers will be available. A due proportion of these will, by simple and reliable means, be cut out of circuit during the consumers' heavy demand hours for other purposes and come on again when that demand is reduced. Approximately half the cooking and the whole of the water and room heating can be done with these off-peak devices; thus they will keep the consumer's maximum demand low, protect him from the penalizing dial of his uniform-tariff meter, and give him the benefit of the low costs of production due to the load factor being increased from 25 to 50 per cent. This may appear a highly imaginative piece of prophecy, but it is nearer realization than may be supposed. Such pending development is bound to have marked effect on the cost of electricity supply for all purposes, especially upon tariffs, and yet we are told with unusual confidence and emphasis that the "tariff problem is settled" and that discussion upon it should be banned by the President. Possibly rather than banning discussion the Institution may afford an opportunity of enlarging upon the possibilities of these off-peak storage supplies at a later date. The two-rate meter and uniform tariff we have ventured to advocate will then be better understood and appreciated.

Somewhat scathing reference was made in the discussion to our advocacy of the use of storage batteries deriving their charging current during the hours of light load and discharging their current on heavy load, thus keeping down the maximum demand and thereby reducing the fixed capital charge. The proposal was referred to as a "horror" and accumulators as "messy batteries," the experience of amateur wireless operators being alluded to as confirmation. To apply such a method in the case of small consumers would obviously be absurd, but in Harrogate two of our largest consumers have employed this method for over 20 years with outstanding success and satisfaction to all concerned. Another large consumer of long standing is introducing the system at present. We therefore consider the recommendation made in our paper to be quite sound and amply justified by long experience.

With the off-peak storage methods already briefly referred to, Mr. Cowan's ingenious but difficult refinements are not called for and his demand for a means of preventing these (extra) units being consumed when the system is fully loaded is entirely met.

Mr. Purse's proposal for control by means of "ripple" currents in the distribution system also loses its significance, as every consumer with an all-electric establishment and off-peak heat storage will himself provide the long-hour advantages and characteristics. Under present conditions of the industry these are attained to a limited extent only, by taking on a large number of

consumers each using current for different purposes during varying times of the day, but who individually are non-users for many hours out of the twenty-four.

Mr. H. M. Sayers (*in reply*): The discussion brought out two principal criticisms of the proposals of the paper. The first is that the " value of service " should be taken account of in tariffs, as well as the cost of supply. The second is that a two-part tariff is easier to formulate, easier to apply, and easier to sell on, than a series of flat-rate tariffs based on the classification of consumers' loads. The first criticism involves general principles. Any commodity or service can only be sold to any individual consumer at a price which the consumer considers to be not in excess of its value to him. The money value of any service or commodity varies greatly as between different consumers and classes of consumers, and the price which anyone will pay depends also upon what he can afford.

Domestic electricity supply is a service the value of which cannot be assessed completely, or even approximately, in terms of money. Cleanliness, comfort, healthfulness, convenience, adaptability, relief from drudgery, are all " values " which cannot be put into money terms; every one is willing to pay some money for them; but the great majority of potential domestic consumers can only pay some limited amount. The people who will obtain the greatest values in this sense are precisely the people who can afford the smallest payment. The wage-earner with a young family whose wife is the mother-housekeeper will get a greater value in comfort, general happiness and relief of drudgery from an all-electric house than the middle-class householder whose means permit the keeping of two or three servants; but the former can afford to pay less for the service.

The price obtainable from any domestic electricity consumer is his own valuation of its advantages compared with alternative means of obtaining the same primary service. This price is not susceptible to calculation by the seller on any principle whatever; therefore I say that the " value of service " basis is not available. A striking instance of this was given by Mr. Rosling's contribution to the discussion. Electric lighting, he said, was worth 7s. per unit to him in clear money terms (saving on house decorations, etc.), a price at which electric lighting could have made no progress at all. Nor could the most persuasive salesman have persuaded one possible consumer in a hundred thousand that any such result was other than the figment of a lively imagination.

A commercial price must exceed the bare cost of supply by the increment of profit which is necessary to remunerate the capital engaged. Such a price will result in the largest profitable sale; for clearly the potential consumers who cannot or will not pay so much are not accessible excepting at a loss; whilst all those who can and are willing to pay that price are accessible. It is true that some of these may be willing and able to pay a higher price, but such higher price will shut out a larger number and probably increase the unit cost. I maintain that the value of service to different classes of consumers cannot be ascertained, but that the cost of supply to such different classes can; it is therefore the practicable basis for fixing tariffs. The differentiation is the proportion of the different purposes of connected load, and the ascertainment is by observation of a sufficient number of cases with similar proportions.

As to the preference generally expressed for two-part tariffs, the following comments are offered: It is admitted that the periodic fixed charge, per annum or per quarter, is intended to represent the fixed-charges element in the cost of supply. It ought, then, to be based upon some feature of the consumers' demand which corresponds to that cost. So far as I can discover, this is not the case in any of the usual two-part tariffs. The favourite rateable-value basis is not defended by anyone as having any necessary relation to the fixed-charges cost of supply. It is therefore not necessary to show that it is a purely empirical basis. It is easy to apply, but the consequences of periodical rating revaluations may cause trouble. It is clearly not equitable. Maximum demand is a fair basis as between consumers having similar load characteristics and some definite diversity factor, not as between consumers with different load characteristics. It is ruled out for that reason; but it is the principle I propose to use, for *each class* of consumer, without the complication of instruments and calculations for individual consumers.

It is said that two-rate tariffs are easier to sell on than a series of flat rates. That depends on the salesman. To sell domestic supply the salesman should advise the potential consumer what he ought to install, and after discussion settle with him what he will have. Then he can quote the appropriate flat rate. Any number of the rates can be quoted, but each in relation to defined proportions of consuming apparatus, lighting, cooking, etc. Such a method of salesmanship will get a better aggregate class of connected load than quoting a rateable value or other irrelevant periodic charge and a rate per unit, regardless of the class and proportion of the apparatus installed.

The charge by classification does not exclude two-part tariffs. The fixed-charges elements in the cost are definitely evaluated by the plan I propose. If it seems better to separate them and levy them by periodic payments it can be done, with the advantage that the amounts are related to the average demands on the system by that class of consumer. Alternatively each consumer may be charged at a high rate for a fixed number of units per quarter, and a low rate for the remainder, the fixed number depending upon the character of the connected load and its magnitude.

The great objection to two-part tariffs for domestic supply is that a large proportion of potential consumers are not able or are not willing to engage to make relatively large quarterly payments. Many of them pay weekly rents; many find rents, rates, and other quarterly payments quite enough to pay in lump sums. To this large proportion of potential consumers the most attractive method of payment is by prepayment meter; and I suggest that generalized domestic electrification depends ultimately upon prepayment-meter methods, which necessitate flat rates; or, alternatively, upon weekly collection, which is too expensive and cumbersome.

I would repeat, with emphasis, that on the selling side the supply industry has to raise system load factors from the prevalent level of between 20 and 30 per cent, to the quite possible level of between 45 and 60 per cent—excluding traction and chemical loads. The field open is that of domestic supply. The method—so far as it depends upon price—is to fix prices in relation to costs, i.e. to load and diversity factors by classes.

I am disappointed at the absence of discussion on the subject of distribution economy illustrated by the table and figure in the paper. It is a subject intimately connected with tariffs, for low rates require low distribution costs; low distribution costs involve good distribution load and form factors; and good distribution load and form factors can be secured only by tariffs which stimulate and by salesmanship which obtains loads of the right character. As Mr. Beauchamp said, "Put down heavy copper and fill it up." But fill it up in time, as well as maximum load. Distribution design for total economy is not a common feature of supply undertakings in this country. It has been a hand-to-mouth process generally. Certainly it has been very difficult to forecast the growth of load both in time and in space. There is evidence that the hand-to-mouth policy persists; and that in many places new distribution work is in progress which cannot give economical results. With effective tariffs for domestic supply it should soon be possible to calculate loads as closely as the water-supply engineer can calculate water consumption and the necessary mains. At this stage of development, distribution should be designed for maximum economy for a reasonable time ahead, just as telephone systems are. The problem is simpler and the risks of mistaken forecasts smaller.

Turning to some individual criticisms, I note that Colonel Vignoles admits that his first impression that discussions on tariffs are inopportune has been corrected by statistics. I suggest that he might usefully reconsider domestic tariffs. His undertaking has the creditable load factor of 35·72 per cent, exceeded by only five undertakings in the current *Electrical Times* list. But, first, he has a tramway supply, and secondly, the sales for private supply are only 80·5 units per head of the population per annum. There is room for improvement. Colonel Vignoles has certainly led his Council in the right direction in respect to domestic supply. I am sure he wishes to go further.

Captain Donaldson (with others) thinks that the high initial rate corresponding to the fixed-charges cost must be based on the lighting demand. I am not sure of this, even now. With generalized domestic electrification the house lighting load is likely to become a mere pimple, and it may not be on the domestic peak at all. Sunday mornings will probably see the domestic peak. Shop lighting, factory lighting, and street lighting are in a different category. Captain Donaldson says that it is useless to attempt to base a demand charge on the cooking and heating load, "because no one knows how it will work in practice." I say: Find out how it works in practice, by observing a sufficient number of consumers to give a fair average. With that knowledge, the base is given. Such tests may possibly show that the lighting connections give a good basis, with a proper multiplier for each class; but I doubt it as a permanent relation.

Mr. Blaikie thinks that I overrate distribution costs (not the "cost of mains") compared with generating costs. The President gave a similar ratio in his Address at the beginning of the current session. I have found such relative costs in many analyses which I have had to make for separating the two classes of costs. Mr. Blaikie has perhaps not noticed that the cost of "units unaccounted for" is a distribution cost which appears in the station expenditure. Distribution costs are even more susceptible than generation costs to diminution by improved load characteristics, but it must be improvement all over the system.

Mr. Cowan quite correctly credits Arthur Wright with the enunciation and application of the principle of charging consumers upon their cost. It was in a paper read before the Municipal Electrical Association at Brighton in 1896. Wright's pioneer work cannot be overrated. It is the basis of every rational tariff. His name is much more generally attached to such tariffs in the United States than in his native country. I very much regretted his absence from the meeting. He could have given some interesting information about supply tariffs in the United States, where the subject is very much alive and the multiplicity of tariffs is relatively as great as it is here.

Mr. Beauchamp is right in saying that we cannot talk about the cost of supplying the individual domestic consumer. But we can find out the cost of supplying classes of similar domestic consumers, and use the averages with such loading as seems prudent, exactly as insurance companies adjust premium rates by ascertained averages. He agrees that none of the present methods of assessing the fixed charge are free from objection. I propose to assess it by trial. Whether it is levied as a periodic fixed charge, a high rate for a minimum consumption followed by a low rate, or a flat rate, is a matter of expediency and detail.

I am grateful to Mr. Kapp for his agreement.

Mr. Purse, I think, really agrees with me in principle, for the power he hopes to get will surely include some way of adjusting the charge to the class, in the sense of proportion of kinds of load, as well as the size of installation. Mr. Purse thinks that there is an inconsistency in the paper, overlooking that on page 854 the item of charge on the connected load is only that fraction of the fixed charges to cover the cost of the individual service, meter, etc. Mr. Purse alludes to the very important matter of the supply of apparatus to the domestic consumer. That is correlative to the matter of attractive domestic tariffs, and just as essential to general domestic electrification. But it is not the subject of the paper.

With Mr. Gill's remarks I am in complete agreement. The experience of a comparable industry is most useful.

Mr. Rosling sets out some quite sound reasons for separating lighting and heavy-current circuits. I have already referred to his statement on "value of service."

In conclusion, I would thank all contributors to the discussion, the value and interest of which is ample reward for starting it. The initiative of the Council in arranging for it is most opportune, in view of the developments in immediate prospect.

THE USE OF INDUCTION REGULATORS IN FEEDER CIRCUITS.

By Laurence H. A. Carr, M.Sc.Tech., Member.

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Summary.

The paper describes the uses and possibilities of induction regulators as applied to feeder and interconnector circuits.

Three types of induction regulator are described, together with their characteristics; the single polyphase regulator, the double polyphase regulator, and the single-phase regulator.

The application of regulators to various types of circuit is considered, first to the supply feeder, secondly to the interconnector between power stations, and then to the ring main or twin feeder.

The effect of regulator impedance is discussed.

Finally, the operation, construction, and control of induction regulators are discussed.

Introduction.

The function of the induction feeder regulator is to provide an additional pressure in an alternating-current feeder, either for raising the voltage at the far end of a simple supply feeder, or for controlling the power factor and in that way assisting the transference of power along a feeder connecting two or more generating stations.

In the United States it is very largely used for this purpose and with the growth of large supply systems and large interconnected groups of systems its use is increasing in this country. It is important to possess a clear knowledge of the characteristics of the induction regulator before laying down the requirements for any given circuit, and it is to discuss the behaviour of the induction regulator under different conditions that this paper has been written.

In general three types of regulators may be considered for use with alternating-current feeder circuits:—

(*a*) The single polyphase regulator.
(*b*) The double polyphase regulator.
(*c*) A bank of single-phase regulators.

The Single Polyphase Induction Regulator.

The polyphase induction regulator is similar both in construction and in theory to the three-phase induction motor at standstill. Such a machine has the characteristic that, depending on the position of the tappings of the secondary coils relative to the tappings of the primary coils, any phase displacement between zero and 360° may exist between the E.M.F. produced by the secondary and the E.M.F. supplied to the primary.

The regulator normally works at standstill, but one part (either the primary or secondary, as may be most convenient) is made to rotate relatively to the other so that any desired phase displacement between the two parts may be obtained from full arithmetical sum to full arithmetical difference. The secondary windings are provided with two terminals to each phase-winding and are connected in series with the line as shown in Fig. 1, the connection being somewhat similar to that of an auto-transformer.

Fig. 2 shows the vector diagram of the voltages (only one phase being shown for clearness), where OA

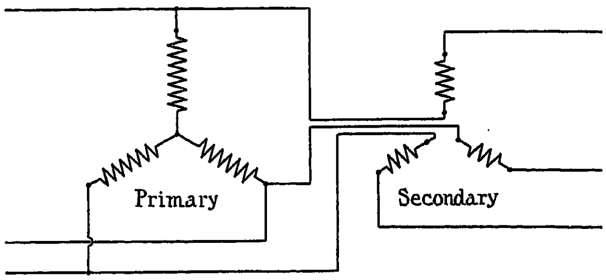

Fig. 1.—Diagram of connections of induction regulator.

is the supply voltage, AB the secondary induced voltage, and OB the resultant is the outgoing voltage applied to the feeder. In this diagram, and in all the succeeding diagrams except Fig. 17, the impedance-drops in the regulator, which are relatively small, are neglected.

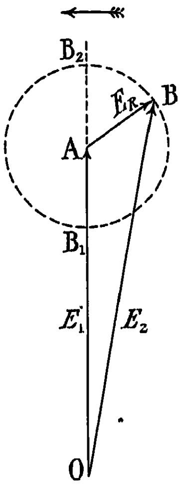

Fig. 2.

The locus of B as the rotor is turned round is a circle with A as centre, and the complete circle corresponds to a movement through two pole-pitches. The limiting values of OB are OB_2, the maximum positive boost, and OB_1, the maximum negative boost.

In practice it is sufficient to move the rotor through one pole-pitch only in order to obtain the full variation

between OB_1 and OB_2, the vector AB travelling either round the trailing semicircle or the leading semicircle shown in Fig. 2, and in general either semicircle can be selected by suitably relating the motion of the rotor to the phase rotation of the primary.

Apart from the magnetizing current and losses of the regulator, the kVA input is equal to the kVA output, and the power factor of the primary circuit is the same as the power factor in the secondary winding of the regulator, which, it should be noted, is usually not the same as the power factor of the feeder circuit, since the E.M.F. induced in the secondary winding is usually not in phase with the line pressure.

This may easily be understood by reference to Fig. 3, the full lines being first considered. Here E_1 represents the supply voltage, E_R the secondary voltage of the regulator, and E_2 the feeder voltage. I_2 is the feeder current at an angle ϕ behind E_2.

The power generated in the secondary windings of the regulator is the vector product of E_R and I_2.

Apart from the magnetizing current, the primary ampere-turns in the regulator must balance the secondary ampere-turns, exactly as in the case of the induction

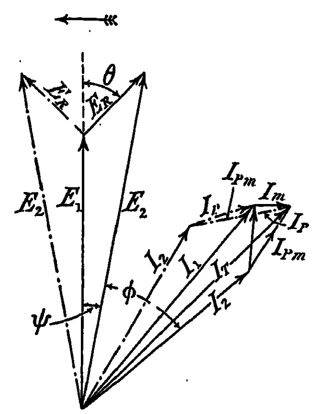

FIG. 3.

motor, and for the same reason, but the ratio of turns is given by the ratio of voltages E_R/E_1. Hence the corresponding load current I_P taken by the primary will be in magnitude equal to $I_2 \times E_R/E_1$ or, in other words, the primary kVA equals the secondary kVA, neglecting the magnetizing current and the losses in the regulator.

The primary kW must equal the secondary kW, therefore the primary power factor equals the power factor in the secondary winding. In other words, if E_R lags behind E_1 by the angle θ, then I_2 lags behind I_P by the angle θ. These considerations enable the primary current I_P and the total current supplied, I_1, to be drawn, the magnetizing current still being neglected.

The two triangles E_1, E_R, E_2 and I_2, I_P, I_1 may then be considered. Since $I_2/I_P = E_1/E_R$, and the angle between I_2 and I_P is the same as the angle between E_1 and E_R, namely $(180 - \theta)$, the two triangles are similar and the two angles at the origin are the same. Therefore the angle of lag between I_1 and E_1 is identically the same as that between I_2 and E_2.

It will be noted that there is a phase lag (angle ψ in Fig. 3) between the E.M.F. on the two sides of the regulator, but the same phase lag exists between the two corresponding currents.

Returning to Fig. 2, it is seen that the same boost could be obtained with the secondary voltage E_R leading E_1.

The chain-dotted lines in Fig. 3 give the corresponding diagram for this alternative position of the regulator giving the same boost.

Including the magnetizing current of the regulator, the total primary current of the regulator I_{Pm} consists of the vector sum of the load current I_P and the magnetizing current I_m, while the total current taken from the supply is I_T, the vector sum of I_2 and I_{Pm}.

It will be seen that the regulator primary current I_{Pm} is not the same for the two positions of the regulator giving the same boost, although the total supply current remains the same. This may appear to be unexpected, but consideration shows it to be due to the fact that the alternative positions of E_R do not and cannot (except at times of maximum boost) make the same angle with I_2, and hence the power factor in the secondary winding of the regulator is different in the two cases. The induction regulator may be further studied by means of a locus diagram (corresponding to the induction-motor circle diagram) showing the variation in the current input at varying loads. Unlike the case of the induction motor, however, a single curve does not suffice unless the conditions under which the regulator is working are laid down, that is to say unless the relationship between the amount of boost and the load current is specified, and the power factor of the feeder current fixed.

In any case, however, the diagram centres round the maximum boost conditions (in which case the two alternative diagrams shown in Fig. 3 become identical).

At maximum boost, with a given angle of lag ϕ in the feeder circuit, the input current may be represented by a line such as PN in Fig. 4 (*a*), composed of two components, PM the magnetizing current, and MN the component equal and opposite to the secondary current multiplied by the ratio of turns.

PE is the applied primary voltage, and MN is inclined at the angle ϕ to PE. Three cases may be considered, corresponding to the three curves drawn in Fig. 4 (*a*).

In each of these cases the feeder power factor is assumed to be constant and the regulator impedance is neglected. In case I (curve I in the figure) the feeder current is assumed to be constant irrespective of the amount of boost. Here the locus of N is a circle, the full circle corresponding to a movement of the rotor through two pole-pitches. The angle θ between MN and any selected position of current MN′ gives the mechanical angle (measured in electrical degrees) through which the rotor must be displaced from the maximum boost position in order to give the conditions represented. This case is seldom, if ever, met with in practice, but the curve is of use, as it gives a comparison of the input required for the same output in kVA at different power factors, since it serves to show the variation in the position of MN with various values of ϕ if the angle θ remains zero.

In the second case, represented by curve II in Fig. 4 (*a*),

the boost required is assumed to be proportional to the feeder current. If the angle ψ in Fig. 3 is small the boost is practically equal to $E_R \cos \theta$. If this equality were absolute, the resulting curve would be a circle on MN as diameter, and it is shown as such in the figure, since the distortion introduced due to the angle ψ is exceedingly small. This diagram corresponds to an interconnector regulator capable of transmitting the feeder current in either direction, in each case supplying the necessary pressure to overcome the line pressure-drop. Since the current reverses at zero boost, the circle on MN as diameter is swept out twice for a regulator movement through two pole-pitches. The boost corresponding to any given current can be quite simply determined by drawing the voltage diagram in a particular manner alongside the current diagram, as illustrated in Fig. 4 (*b*). It will be noted that in this diagram the rotation of the vectors with time is clockwise, that is to say in the contrary direction to Fig. 4 (*a*). The feeder current is drawn vertically, OI representing the current at maximum boost. The supply E.M.F. (OA in the diagram) is therefore parallel to MN in the current diagram. For any position of the current vector, say along MN′, it is only necessary to draw the regulator voltage AB parallel to MN′ to give the E.M.F. supplied to the feeder, namely OB.

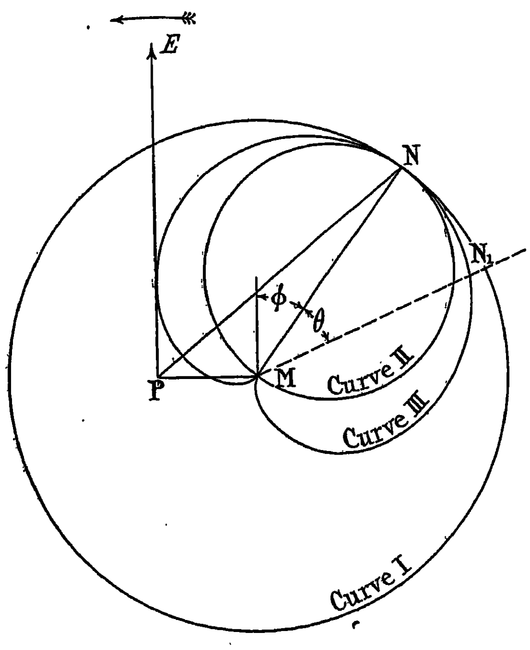

Fig. 4 (*a*).

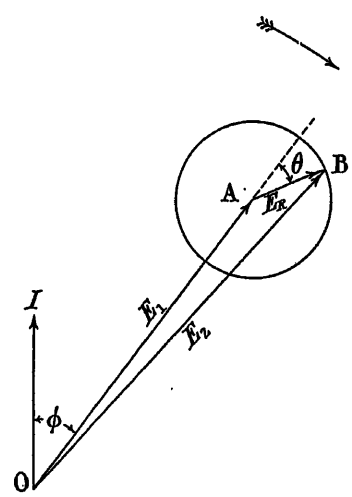

Fig. 4 (*b*).

The third case considered, curve III, represents the case where the transformer or other supply ratios are so chosen that the regulator is required to give its full back pressure at no load, the whole range of the regulator being available for raising the voltage as the load comes on. In other words, at no load there is full negative boost ("buck") on the regulator, at half load there is neither negative nor positive boost, and at full load there is full boost. This arrangement gives the smallest regulator for a given supply feeder service. The resulting curve is swept out once as the regulator is moved through two pole-pitches.

In each case shown in Fig. 4 (*a*) as the rotor of the regulator moves from the full boost position the diagram may be swept out in a right-handed or in a left-handed direction, depending on the direction in which the rotor is turned.

Except in the case of an interconnector regulator loaded as described in case II, where the whole diagram is necessarily swept out, it is advantageous to sweep out the diagram in a left-handed direction, since in that case the primary current and hence the primary copper losses are less than if the diagram be swept out in the other direction. This favourable relation is obtained if the rotor is moved from full boost position in the same direction as the rotating magnetic field when the rotor carries the secondary winding, and in the opposite direction if the rotor carries the primary winding. This phasing-out must be checked on site, as it cannot be prearranged at the manufacturer's works, any more than can the direction of rotation of an induction motor, unless the phase rotation of the leads to which the regulator is to be connected is known.

Double Polyphase Regulators.

In certain cases, to be discussed later, the phase-shift between the supply voltage and the delivered voltage (that is to say the angle ψ in Fig. 3) is objectionable. To overcome this defect the double polyphase regulator is used. This consists of two regulators each of half the total capacity, with the secondaries connected in series and arranged so that the phase-shift of one neutral-

izes the phase-shift of the other. The voltage vector diagram of this arrangement is shown in Fig. 5, the regulator impedance being neglected, where OA is the supply E.M.F. and AB_1 and B_1B_2 are the E.M.F.'s of the two halves of the regulator.

As the rotors of the regulators are moved, the vector AB_1 turns in a clockwise direction, while the vector B_1B_2 turns in a counter-clockwise direction. The resultant voltage OB_2 is therefore always in phase with OA, the supply voltage, and varies from OC_2 as a maximum [equal to $OA + (AB_1 + B_1B_2)$] to OC as a minimum [equal to $OA - (AB_1 + B_1B_2)$]. In order to obtain this effect, either the two rotors may be made to rotate in the same direction while the two rotating fields rotate in opposite directions, or the rotors may move in opposite directions while the fields rotate the same way. The former is the more usual in practice.

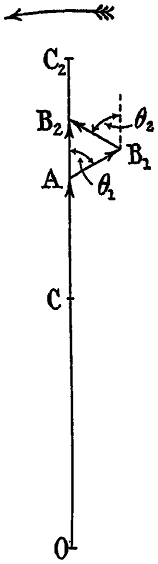

FIG. 5.

In either case, referring back to Fig. 4 (*a*), it will be seen that while one half of the regulator sweeps out the right-hand side of the particular locus diagram concerned, the other half of the regulator will be sweeping out the left-hand side. In other words, for the double regulator one half automatically takes up the most favourable conditions, the other half the unfavourable conditions.

This diagram also shows that except at times of maximum and minimum boost the two primary windings do not carry the same current, and consequently they must be connected in parallel and not in series.

The Single-Phase Induction Regulator.

The single-phase regulator is principally used on single-phase circuits, but may also be used in a bank of three units on a three-phase system. In the single-phase regulator the magnetic field is purely alternating, and as the secondary winding is gradually turned out of the axis of the magnetic field, the E.M.F. induced in it is reduced without any phase lag (apart from that due to the impedance of the windings). The conditions here are thus different from those in the case of the single polyphase regulator, and are more akin to those of the double polyphase regulator.

At the same time, the single-phase regulator has one important characteristic which must not be overlooked in the design, and that is that in the position of no boost, and if no special precautions are taken, the secondary current will induce a very large flux in the regulator at right angles to the main flux. This will cause the reactance of the secondary winding to be exceedingly high, thus forming an impedance in the feeder circuit. To overcome this difficulty an auxiliary winding short-circuited upon itself is placed upon the primary member at right angles to the primary winding. This has the effect of keeping down the reactance in the secondary circuit to a practically constant value.

In a bank of three single-phase regulators, if the load is balanced between the three phases and the regulators are mounted so that each gives the same boost, each primary requires the same current, and hence the primaries may be connected in star. In this case the

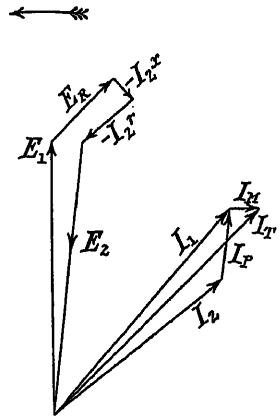

FIG. 6.

voltage induced in the secondary winding will be in phase with the phase voltage and not with the voltage between the outers.

The three regulators can be, and usually are, geared together mechanically so as to operate simultaneously. Owing to the small size of each unit where single-phase regulators are used, and on account of the losses in the auxiliary or damping winding, the efficiency of a single-phase bank is usually lower than that of the corresponding polyphase regulator, while in addition its first cost is generally higher.

Feeder Circuits.

In an ordinary feeder circuit the function of the induction regulator is to provide an E.M.F. to overcome the impedance drop in the feeder in order to keep the voltage constant at the far end.

It is not necessary for this added voltage to be exactly in phase with either the applied voltage or the feeder impedance drop, so long as the outgoing voltage from the regulator is of the correct magnitude. Fig. 6 shows

the vector diagram* of a feeder circuit supplied by an induction regulator, which is shown as giving only about half its maximum boost, in order to emphasize the phase differences. Here E_1 represents the supply voltage, and E_R the regulator voltage, giving the total voltage of E_2 applied to the feeder.

I_2 is the feeder current, I_P the regulator primary load current, I_M the regulator (primary) magnetizing current and I_T the total current supplied from the generating plant.

Interconnector Circuits.

Where two power stations are connected together by a feeder the power supplied by each station will depend solely on the power supplied to the prime movers. Under these conditions, power can be supplied at will from station to station, but if the voltage at each end of the line is to be kept the same, the power can only be transmitted at a low leading power factor. This

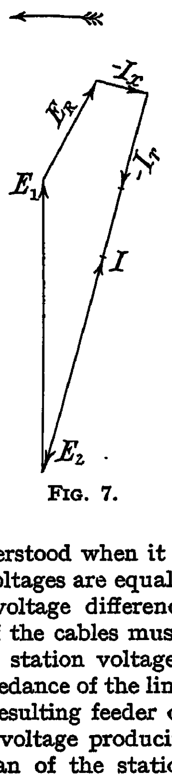

Fig. 7.

may be readily understood when it is remembered that since both station voltages are equal or are equalized by transformers, any voltage difference which can exist between the ends of the cables must be at right angles to the mean of the station voltages. This would not matter were the impedance of the line purely inductively reactive, since the resulting feeder current would be at right angles to the voltage producing it, and hence in phase with the mean of the station voltages. Since, however, the resistance is usually greater than the reactance, the current will be more nearly in phase with the voltage across the feeder, lagging at most, say, 30° behind it (corresponding to a ratio of $x/r = 0 \cdot 578$), which means that the current vector is 60° away from the mean of the station voltages.

Since cos 60° $= 0 \cdot 5$ it follows that the interconnector when fully loaded as to its current is only transmitting half of the power which it should be able to carry. To utilize the interconnector to its full, an induction regulator (or other adjustable boosting apparatus) is required to provide a voltage which will just overcome the impedance drop in the interconnector when the current corresponding to the power transmitted is flowing at the desired power factor.

With an induction regulator, the power factor in the interconnector may be maintained at unity at any load without necessitating any alteration in the voltage of either station. Alternatively, with constant station voltage, the magnetizing current may be shared between the stations as desired (the interconnector being loaded at the corresponding power factor) by adjusting the amount of boost given by the regulator.

Fig. 7 illustrates the transmission of power from station to station where a regulator is installed in the interconnector, the power factor being unity at the receiving end. E_1 is the busbar voltage of the station supplying power, E_2 the busbar voltage of the station receiving power, E_R the regulator E.M.F. (applied at the sending end in this instance), I the interconnector current, and x and r the interconnector reactance and resistance respectively. The regulator primary current is omitted from this diagram.

Fig. 6, which was drawn for the case of a dead-ended feeder, also applies to the case of the interconnector, and represents the transmission of power from station to station at a lagging power factor. In this case I_2 is the current transmitted along the interconnector, while the total current I_T necessary to be supplied by the sending station is also shown. It should here be emphasized that it is only by the aid of an induction

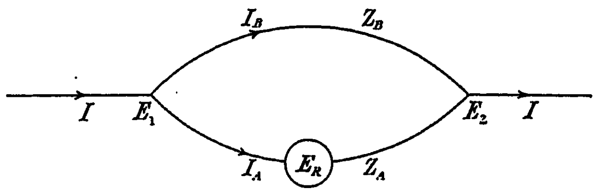

Fig. 8.

regulator or a similar device that the operators in the power stations can have complete control not only of their own voltage and power supply but of the power transmitted from station to station and of the power factor at which it is transmitted. Further, the induction regulator, though expensive, is the only practical device which permits the control to be gradual.

Where there is no other connection between the two stations than the interconnector containing the regulator, the regulator may be of the single pattern since no difficulty is introduced by the fact that one station may slightly lead the other in phase.

Regulators on Ring Main or Twin Feeder Systems.

Special consideration must be given to the case where it is required to insert a regulator in a feeder, the ends of which are connected together electrically by another feeder or system of feeders. The simplest case to consider, which will be used as an example, is where only two feeders supply the same point, feeder A containing the regulator, while feeder B is connected direct to the receiving end without any regulator being inserted, as illustrated diagrammatically in Fig. 8.

* In this and the succeeding vector diagrams the convention is adopted that "the sum of the voltages in a circuit is zero"; consequently an impedance drop is represented by $-I(r + jx)$, while an E.M.F. representing a motoring action, or absorption of electrical power, is in the contrary sense to $I \cos \theta$.

Let E_1 = E.M.F. at supply end.
E_2 = E.M.F. at receiving end.
E_R = regulator E.M.F.
I = total current transmitted = vector sum of I_A and I_B.
I_L = full-load value of I.
I_A = current in feeder A.
I_B = current in feeder B.
$Z_A = \sqrt{(x_A^2 + r_A^2)}$ = impedance of feeder A.
$Z_B = \sqrt{(x_B^2 + r_B^2)}$ = impedance of feeder B.
$\frac{x_A}{r_A} = \frac{x_B}{r_B} = \tan\zeta$

By suitably adjusting the regulator, E_2 may be maintained equal in value to E_1 whatever the magnitude and phase of the current I. It is desired to determine how the total current splits up between the two feeders in these circumstances.

The conditions and the solutions are identical whether the feeder system is dead-ended, supplying power to a load; or whether it links up with the busbars of another station, supplying power to it.

For constant power factor and varying load, if the regulator impedance be neglected, a simple geometrical construction will give the desired solution in the form of the locus of I_A, the current in feeder A, if the power factor is measured with reference to a vector E_M located midway between the vectors representing the voltages of the two stations as drawn in Fig. 7. This gives the solution for the mean of the two cases where the regulator is situated at the receiving and at the supply end of the line respectively. Taking first the case of the single regulator, where E_R is made numerically equal to $I_L Z_A$, the magnitude of the regulator voltage remains constant, but its phase angle is varied as load comes on, in order to meet the required condition that E_2 shall be numerically equal to E_1.

Fig. 9 gives the vector diagram of the E.M.F.'s present and leads to a simple graphical method by means of which the current locus may be determined as follows:—

In Fig. 9 let OA $= E_1$
BO $= E_2$

AB must necessarily be at right angles to E_M.

Then if AC $= E_R$
CB $= -I_A Z_A$ and AB $= -I_B Z_B$.

Extend AB to D and cut off BD such that

$$\frac{BD}{AB} = \frac{Z_A}{Z_B} = \frac{-I_B Z_A}{-I_B Z_B}$$

Join CD
Then CD = CB + BD (vectorially)
$= -I_A Z_A - I_B Z_A$ (vectorially)
$= -IZ_A$

CD therefore always remains parallel to itself for any given case of constant power factor, while E_R moves through the arc of the circle.

By dividing the vectors in this voltage diagram by $-Z_A = -(r_A + jx_A)$, treated as a complex number, that is to say by dividing the numerical values by $\sqrt{(x_A^2 + r_A^2)}$ and turning the vectors in a clockwise direction through the angle $(\frac{1}{2}\pi + \zeta)$, where ζ = arc tan x/r, the current diagram (Fig. 10) is obtained, where the line CD representing the current I corresponds to the line CD representing $-IZ_A$ in Fig. 9.

To find the current conditions for any given load I, the circle of radius E_R/Z_A must be struck and the line

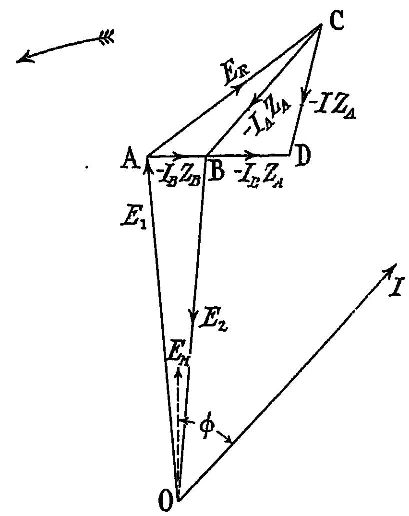

FIG. 9.

$(I_B + I_B Z_B/Z_A)$ drawn from D, the termination of I, making an angle of ζ with the horizontal axis. This line must be cut off where it cuts the circle at A, and DA divided at B in the proportion Z_A/Z_B as shown in Fig. 10. This point B gives the position of the end of the vector I_A. By drawing a series of such points the locus of I_A can be drawn, and I_B which makes the constant

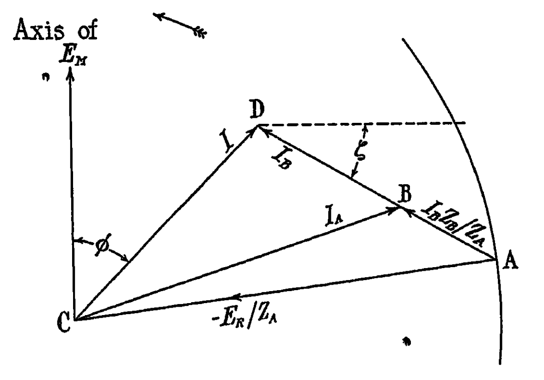

FIG. 10.

angle ζ with the horizontal can be filled in where desired.

It is seen that the relation of ζ, the natural angle of lag of the feeder, to ϕ has an important bearing on the shape of the diagram, and a critical case occurs when $\zeta = \phi$, the angle between I and I_B being in this case 90°.

The first example is taken under these conditions and is drawn for $\phi = \zeta = 36° 52'$, that is to say,

cos $\phi = 0{\cdot}8$ and $x/r = 0{\cdot}75$. The simplest relation between the feeder impedances is also taken in this example, namely $Z_B = Z_A$.

Fig. 11 is drawn for this case and shows the locus of I_A. It will be seen from the diagram that at no load (where $I = 0$) both I_A and I_B equal $\frac{1}{2}I_L$. In other words, at no load, due to the phase shift introduced by

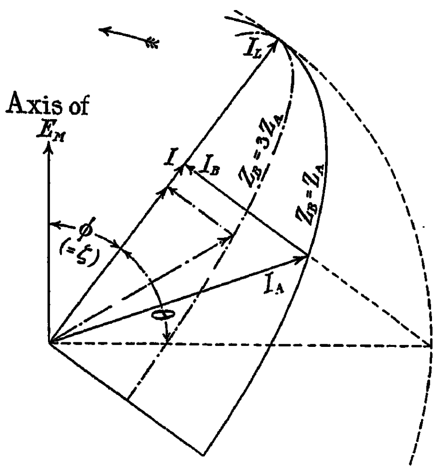

FIG. 11.

the regulator, there is a circulating current in the feeders equal to half the full-load current. It is for this reason that single polyphase regulators are not recommended for use in ring-main systems.

The values of the currents I_A and I_B for varying values of I (in terms of I_L) are plotted in Fig. 15, whilst

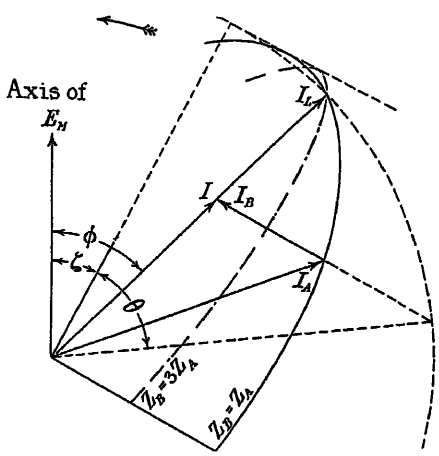

FIG. 12.

the values of total copper losses $(I_A^2 + I_B^2)$ are plotted in terms of I_L^2 against varying values of I in Fig. 16. If Z_B is greater than Z_A the circulating current is reduced, and the chain-dotted curve in Fig. 11 is drawn for $Z_B = 3Z_A$, the ratio of x/r and the other conditions remaining as before. In this case the no-load circulating current is only one-quarter of the full-load current.

Fig. 12 is drawn for a single regulator when ζ is not equal to ϕ. Here cos ϕ is taken as $0{\cdot}70$ ($\phi = 45° \, 34\frac{1}{2}'$) and $\zeta = 30°$. The full curve represents the current locus when $Z_B = Z_A$, and the chain-dotted curve represents the locus when $Z_B = 3Z_A$. The currents and losses corresponding to the full lines ($Z_B = Z_A$) are plotted in Figs. 15 and 16 respectively alongside those of the previous case.

Fig. 12 shows that at full load, θ, the angle through which the axis of the regulator is turned from its "maximum boost" position as understood in the previous sections of the paper, is not zero but is $(\phi - \zeta)$. The reason for this is that the regulator must be turned through such an angle that its voltage when acting on the impedance of the feeder will produce a current in phase with the load current I. This figure also shows that if the regulator be moved in the other direction the diagram is not symmetrical round I_L, and that in one position the regulator, though only producing a voltage equal to $I_L Z_A$, will keep the voltage constant when a current rather greater than I_L is flowing.

Turning now to the double regulator, the conditions are different. Instead of E_R swinging round to meet the conditions of load, its phase angle remains constant

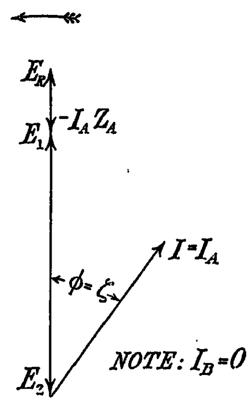

FIG. 13.

(for simplicity assumed in phase with E_M), and only its magnitude varies.

In the critical case where $\zeta = \phi$, the whole diagram collapses into a line as shown in Fig. 13, and I_B is zero throughout. There is no circulating current, and no loss introduced due to it.

Where ζ is not equal to ϕ, however, the regulator E.M.F. is not in exact phase with the impedance drop caused if I flowed entirely through feeder A, and consequently a small circulating current is always present.

A construction very similar to that of Fig. 10 can be used and is shown in Fig. 14, using the same constants as in Fig. 12. In this case an axis CA is drawn making an angle of ζ with the vertical axis. A perpendicular DA is dropped on this axis from D, where CD represents the total current I_L.

DA is cut in B in the proportion

$$DB/BA = Z_A/Z_B$$

Then $I_A = CB$.

If the figure is drawn for full load, then for any other load the triangle is similar and CB is itself the locus of the vector I_A. Consequently for any given case, I_A and I_B bear a constant relation to I.

Since CA represents E_R/Z_A it follows that

$$\frac{E_R}{Z_A} : I = \mathrm{CA} : \mathrm{CD}$$

or

$$E_R = \frac{\mathrm{CA}}{\mathrm{CD}} I Z_A$$

In other words, the value of E_R required is slightly less than IZ_A, since the current passing along feeder B has

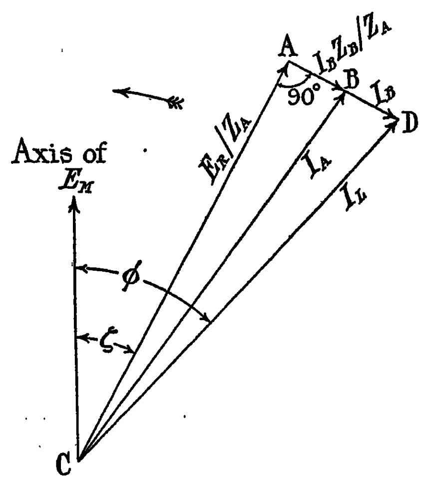

FIG. 14.

a small component in phase with I. Fig. 15 shows how the current divides into I_A and I_B in the four foregoing cases, while Fig. 16 shows the comparative losses where unity is taken to be the loss occurring when I_L flows along feeder A with feeder B open-circuited, the losses in the regulator itself being neglected.

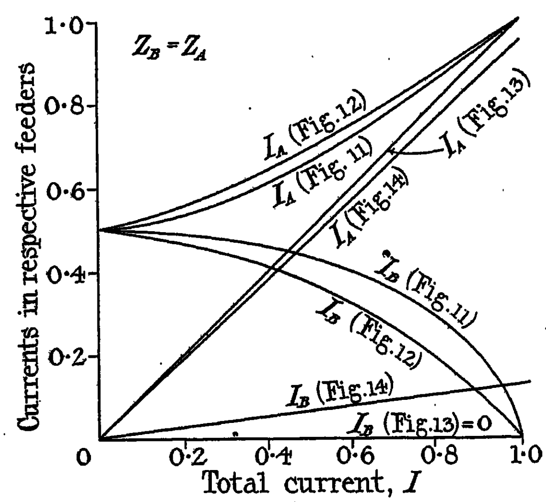

FIG. 15.

As single-phase regulators have, in common with the double regulator, no phase-shift apart from that due to their own impedance, they give the same curves as the double regulator. It is seen that except in the critical case where ζ (the natural angle of lag of the feeder) equals ϕ (the angle of lag at which current is to be transmitted), the double regulator does not give perfect results. Since usually, however, ζ is of the same order as ϕ, this slight lack of perfection is not of very great importance.

To attempt to adjust the angle of boost of the double regulator so as to ensure that ζ follows ϕ (which might be done by turning the two rotors independently, or by the use of a differential, or by the rotation of the stators in addition to the rotors) appears to be an additional complication that is not worth considering, particularly as in practice ϕ does not usually remain constant, and a considerable number of instruments would be necessary to inform the operator as to the exact conditions in the circuit and the exact steps to take to adjust the phase angle as well as the magnitude of the boost from time to time.

REGULATOR IMPEDANCE.

The effect of regulator impedance on the secondary E.M.F. is two-fold. First it causes a variation in the

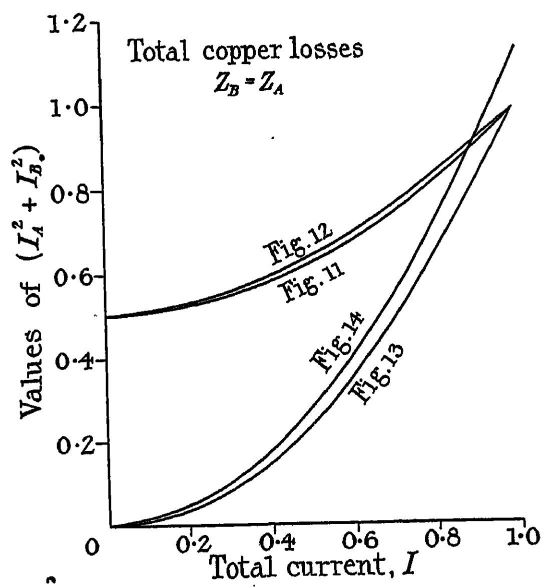

FIG. 16.

terminal secondary E.M.F., and secondly it causes a variation in the phase angle of the secondary E.M.F.

This can be more easily understood by reference to Fig. 17, where

E_1 = primary E.M.F.,
E_R' = secondary E.M.F. referred to the primary,
I_{PM} = primary current,
I_M = magnetizing current,
I_2' = secondary current referred to the primary,
r_1, x_1, Z_1 = resistance, reactance, and impedance of the primary, and
r_2', x_2', Z_2' = resistance, reactance, and impedance respectively of the secondary referred to the primary.

As the phase and magnitude of I_2' vary, so the position and magnitude of E_R vary, and if the current in the secondary winding of the regulator be leading with respect

to the voltage generated in it [see Fig. 4 (*a*)] it is possible for E'_R to be greater than E_1. It is also possible for E'_R to lead E_1.

In general, however, at full load, with lagging currents E'_R will be less than E_1, and this drop must be allowed for in the design of the regulator. The open-circuit voltage is therefore larger than the rated voltage of the machine. Further, since the numbers of both the primary and secondary conductors must be whole numbers, the exact ratio may be difficult to obtain in the design office, with the result that a little extra margin is provided in the regulator.

The term "over ratio" is generally used to represent the excess of the actual no-load secondary voltage over the rated secondary voltage. This variation in the magnitude of the secondary E.M.F. with load causes a slight inaccuracy in the preceding geometrical diagrams, but the effect is only small. The small phase difference between E'_R and E_1 also causes a slight inaccuracy in

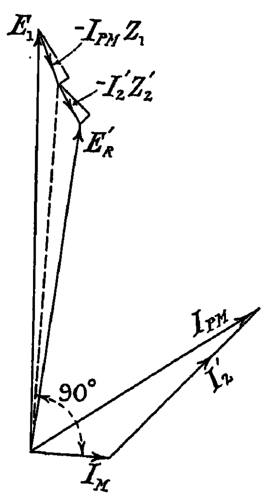

Fig. 17.

these diagrams, since with the single regulator the phase difference between the secondary and primary E.M.F.'s is not exactly equal to θ, but is only approximately so. In practice the only effect of these two inaccuracies is that usually the rotor has to be moved mechanically by a degree or two more than would correspond to the angle θ in the various diagrams.

In the double regulator the lags introduced by impedance in the two halves do not cancel out, and consequently the secondary E.M.F. is not quite in the same straight line as the supply E.M.F., and this is also the case with the single-phase regulator. The effect of this in a divided circuit is to cause an apparent slight increase in the angle ζ. In practice, however, the effect of these slight inaccuracies in the geometrical theory may usually be neglected.

The losses in a regulator are important since they reduce the overall efficiency of transmission, and particularly since the iron losses of the regulator must be supplied during the whole time that the regulator is in circuit.

The full-load losses of a regulator (including the so-called "load losses") vary from about 4 per cent of the kVA in a large regulator to about 8 per cent in a small one. On a 0·8 power factor circuit at full load these figures correspond, with a regulator giving a boost of ± 10 per cent, to losses of one-half of 1 per cent and 1 per cent respectively of the total power transmitted.

Operation and Control of Induction Feeder Regulators.

In all but the smallest sizes, feeder regulators are made of the oil-immersed type, usually self-cooled, but occasionally in the largest ones the oil is water-cooled.

The tanks are of standard transformer tank design and either circular or rectangular in plan.

The regulator is usually arranged with its axis vertical, the operating gear being mounted on top. This operating gear consists of some form of reduction gear, either single worm, double worm, or single worm and spur gear, driven either by a handwheel or by motor.

One worm at least is usually made of the non-reversing pattern, but in the majority of cases a brake is also fitted. This not only assists in stopping the operating motor, but also helps to prevent the regulator from creeping back due to vibration or any other cause. Small regulators are frequently fitted with a permanent brake, the extra power required to operate the regulator with the brake still on being exceedingly small.

Small regulators may be hand-operated where they can be conveniently located alongside the switchboard. The majority of regulators are, however, motor-operated. In this case limit switches are provided to prevent the motor from turning the rotor far enough to bind on the safety stops. The brake in this case is usually electrically operated, releasing when current is switched on to the motor, just as in the case of a crane.

The operating motor requires a low-tension supply (usually alternating current), a squirrel-cage motor being used, although a d.c. operating motor may be employed where convenient. In either case the motor is usually switched straight on the line.

For hand control, the switchgear controlling the operating motor is operated by hand or by means of push-buttons. For automatic working the motor circuit is closed by a contactor controlled by a voltage-regulating relay, two contactors being provided, one for each direction of rotation of the operating motor.

Where an automatically operated regulator is installed at the supply end of a feeder, a "line compensator" is required in order to keep the pressure constant at the far end. This line compensator consists of a resistance and reactance set (by trial if necessary) to correspond to the line resistance and reactance. It is fed through a pair of current transformers and is arranged to reproduce in miniature the drop in the line, both in relative magnitude and phase angle. It is inserted in the circuit of the voltage-regulating relay, which thus responds to the voltage at the far end of the line.

The full diagram of connections for such an automatically controlled motor-operated regulator is shown in Fig. 18. The voltage-regulating relay can be set so as to ensure that the voltage at the end of the feeder shall

not vary by more than 1 per cent from its mean value. In practice it is frequently found advisable to increase this allowance to $1\frac{1}{2}$ or even 2 per cent in order to prevent the regulator from hunting in case of slight variations of supply voltage or heavy fluctuation of load.

The time taken for the regulator to operate, following a change in the voltage, is very small and depends on the gearing, which is usually designed to operate the regulator rather more slowly in the case of the larger regulators. Average figures obtained from several makers indicate that a ± 10 per cent regulator will move over from full negative to full positive boost in from 20 to 40 seconds.

The time of starting up is negligible. Oscillograph tests on a recent 346 kVA automatic regulator show that the operating motor reached full speed within 1/5th sec. of the operation of the voltage-regulating relay, while a similar period covered the stopping of the motor after the voltage relay had opened.

Apart from the control gear, an induction feeder regulator is usually installed without any switchgear at all. It is permanently connected in the feeder circuit and is alive whenever the feeder is alive. Should it be essential that switchgear be provided to isolate the regulator without breaking the feeder circuit, this can be conveniently arranged by a series of oil switches.

The double regulator, if turned to the "no boost" position, may safely be short-circuited on the secondary side prior to cutting out.

With the single regulator this is not the case, and it is necessary to short-circuit the secondary winding through a suitable reactance, isolate the regulator, and then short-circuit the reactance. On account of the reliability of the induction regulator, however, it is not usual to install any such isolating switchgear.

The cost per kVA of an induction regulator varies over wide limits depending on output, voltage and periodicity. Relatively large three-phase regulators for 50 periods may, however, be purchased * for from £3 to £4 per regulator kVA, this figure including all automatic devices. On a ± 10 per cent regulator this corresponds to from £0·3 to £0·4 per kVA supplied.

The principal field for the induction feeder regulator is in interconnector circuits, where the boost is required to be gradual and capable of very fine adjustment, and in supply feeder circuits where boosts greater than 5 per cent are required. Below this figure the single-step boosting transformer, giving a boost of from 3 to 4 per cent, besides being cheaper, will usually do all that is required without too great a complexity of switchgear. Above this figure the multi-step boosting transformer is a possible rival, but on account of the complication and expense of the switchgear, and tappings necessary to allow of the boost to be altered without breaking the feeder circuit, its installation is not looked upon with much favour either in this country or in the United States.

* At the date when the paper was written.

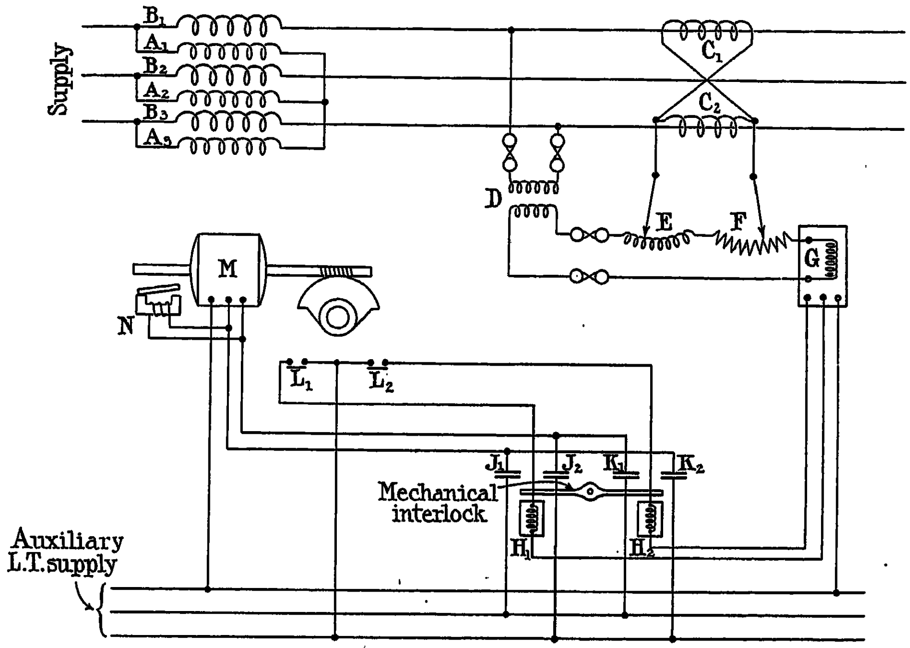

FIG. 18.—Diagram of connections of automatically controlled induction regulator.

A_1,A_2,A_3 = primary windings of induction regulator.
B_1,B_2,B_3 = secondary windings of induction regulator.
C_1,C_2 = current transformers.
D = potential transformer.
E = reactance leg of line compensator (adjustable).
F = resistance leg of line compensator (adjustable).
G = voltage-regulating relay.
H_1,H_2 = operating coils of double-pole contactors.
J_1,J_2 = double-pole contactor.
K_1,K_2 = double-pole contactor.
L_1,L_2 = limit switches (normally closed).
M = operating motor.
N = brake.

Discussion before the North-Eastern Centre, at Newcastle, 26 January, 1925.

Mr. W. G. Bass: The author has succeeded in making a very useful contribution to the subject of induction voltage-regulators. He has, however, set out to describe the uses and possibilities of induction regulators as applied to feeder and interconnector circuits, and in this I do not think he has been so successful. The general subject of feeder voltage-regulation covers so wide a ground that a comprehensive treatment of it cannot be made within the limits of a paper which confines itself principally to the description of one type only of feeder voltage-regulator. On page 868 the author states that "the induction regulator, though expensive, is the only practical device which permits the control to be gradual" and in the last paragraph of the paper he says, "the principal field for the induction feeder regulator is in interconnector circuits, where the boost is required to be gradual and capable of very fine adjustment, and in supply feeder circuits where boosts greater than 5 per cent are required." At one time apparently the gradual control was deemed to be a most desirable property of a feeder voltage-regulator. In an endeavour to approximate to it step-switch regulators were designed many years ago to give a boost of 10 per cent in no less than 14 steps. Actually, in operation it has been found that steps of less than 3 per cent are not necessary to secure an effective control of the current transmitted in parallel feeders. Also, gradual control is not necessary in the case of regulators for use in low-pressure circuits. Rapid variations of 2 per cent in the voltage are not detected by the eye and do not give cause for complaints by consumers, therefore a step-switch regulator which boosts the voltage in steps of 2 per cent can safely be used. The gradual-control feature of the induction regulator therefore not being of great practical use, there is no point in buying an expensive type of regulator which provides it. This means that the other types of regulator are in competition with the induction type, and in the matter of price the latter is invariably at a disadvantage, particularly in those cases where phase-shift is objectionable and the double polyphase type has to be used. I have in mind one job an induction regulator for which was quoted at a price 200 per cent higher than that quoted for a contactor-type regulator to do the same duty. The reduction in the number of steps has the effect of considerably cheapening the step-switch regulator. Further, switchgear difficulties are considerably reduced in the modern arrangement of this regulator, the switchgear being connected in a comparatively low-voltage circuit. The system permits of the use of standard switchgear over a wide range of booster kVA and voltage, and effects a further saving in cost. On this account the step-switch regulator is used to a very considerable extent in feeders which require a boost considerably greater than 5 per cent. As an example of this the Newcastle Electric Supply Co. are now installing in an 11-kV feeder a step-switch regulator which will give a boost of 36 per cent. Where the operation of the regulator is frequent the step-switch type suffers, but in this case the contactor type is the cheaper alternative and one which promises to be altogether more satisfactory. It employs standard contactor gear which is of very robust construction and capable of thousands of operations before the contacts have to be renewed. A further point bearing on the question of cost is not discussed by the author. It is a difficult matter to insulate conductors in slots for a voltage greater than 13 kV and it is therefore necessary in e.h.t. feeders to use step-down and boosting transformers for the shunt and series windings respectively of the induction regulator. In this case the difference in cost between the two types of regulator is therefore the difference between the induction regulator in the one case and the switchgear in the other. If the range of boost is not excessive the switchgear will prove to be the cheaper, particularly if phase-shift has to be avoided and the double regulator used. Where a wide range of boost is required it may be economical to use an induction regulator in conjunction with a step-switch type, the number of steps on the latter being reduced to a minimum and the induction regulator boosting between the steps. On account of the smaller range of boost required of the induction regulator in this case it is possible that the phase-shift introduced by a single regulator would not be sufficiently great to prove objectionable and, therefore, the double regulator would not be necessary. I should be glad to know whether the author has considered this combination of the two types for feeder voltage-regulators. Another point bearing on this question of cost is the characteristic of the induction regulator that it gives a negative as well as a positive boost and as much of the one as of the other. When the regulator is used in conjunction with a transformer it may be possible so to fix the voltage ratio of the latter that the negative boost of the induction regulator can be used. When used as a feeder voltage-regulator, however, the negative boost is useless, so that the purchaser is paying for twice the booster kVA required. I have wondered whether it would be possible to avoid this by connecting in series with the shunt winding a series winding which would have the effect of giving a permanent boost of one half the total. The remaining half, which would be variable, would be so applied as either to boost up or buck against this permanent boost. What is the author's opinion of this proposal? One point which is not touched upon in the paper is the capability of the induction regulator to withstand the stresses resulting from the passage through it of the short-circuit current of the feeder in which the regulator is installed.. This may be, depending upon the circuit impedance, more than 20 times the normal full-load current, and it is most essential that a feeder voltage-regulator be capable of withstanding the resulting stresses. It is possible to provide for this condition in the case of the step-switch regulator, and I shall be glad to have the author's assurance that it is also possible in the case of the induction voltage-regulator. The author does not refer to the three-wire regulator. In networks which have been changed over from direct current to single-phase three-wire alternating current it is possible that such regulators

will be of use. They are cheaper than the alternative two single-phase regulators, one installed on each side of the neutral, and it would have been of interest if the author had described them together with their characteristics. Their use is limited, I believe, to circuits in which the out-of-balance is not excessive, say less than 10 per cent, and I should be glad if the author would confirm this. The automatic operation of single-phase regulators leads to difficulties. In the section dealing with automatic operation the author assumes a convenient auxiliary low-tension supply and the use of a squirrel-cage motor. It should, however, be assumed that no independent source of supply to the motor can be provided. This is a quite reasonable assumption to make as it may not be possible to provide it under any circumstances whatsoever, and if possible it may be altogether too costly. Therefore, with the regulator for use in a single-phase three-wire circuit a single-phase motor must be provided. The induction type has not proved suitable, so far as my experience goes. The most suitable characteristics for this motor are those of the commutator type. In addition it must be capable of very frequent starting up. A satisfactory motor having these properties is difficult to obtain and I should particularly like to hear what the author has to say with reference to such motors, which form a most important link in the equipment of the single-phase automatic feeder voltage-regulator.

Mr. A. W. Crompton: I agree with the author that with the increase in the number of a.c. lighting networks and also in the schemes of interconnection, etc., the need for regulators is greatly extending. Unfortunately, neither the step type nor the induction type has reached that stage of development which meets all requirements. The comparative cost of the induction type as against the step type is decidedly in favour of the latter. The largest induction-type regulator referred to (1 750 kVA) is not large enough to deal with the permissible loading of some main transmission lines. Incidentally there appears to be a certain amount of laxity amongst operating engineers when referring to the rating of regulators, the correct figure being of course that based upon the maximum voltage boost and not upon the line voltage. The boost given for a certain relative position of the stator and rotor appears to depend upon the power factor of the load supplied. The same simplicity of operation does not therefore obtain as with the step type, in which the steps can be numbered to correspond to definite voltages. The chief advantage of the induction regulator in providing a means of varying the voltage very gradually would appear to be of great utility in many ring-main systems, enabling full use to be made of the copper. For example, in the case of a ring main where one side of the ring may be fully loaded due to load near the power station, the other side may only carry a comparatively small load due to the distance away of the first substation. Reference is made to the reliability of the induction regulator, but unfortunately this does not apply to the automatic control gear, and it would certainly appear advisable to provide means of isolating the regulator so that during or after the repair of any essential part of the gear the regulator may be operated clear of the circuit in which it is normally used.

Mr. R. J. H. Beaty: The fitting of tappings to the main transformer is a makeshift that can be tolerated where the power is small and the pressure moderate, but engineering instinct and experience tells one that it would be bad practice when dealing with a large power at extra high pressure. In such a case a simple boosting transformer should be connected in series with the feeder and have its primary fed from either an induction regulator or a transformer with tapping switch. With this arrangement, if a short-circuit occurs on the regulating device the boost will simply be lost, but the feeder need not be cut off; whereas with tappings on the main transformer, if a short-circuit occurs on the tapping switch or its connections the load will be lost and possibly the transformer as well. The series transformer could be insulated so that the risk of a breakdown to earth would be extremely small, and a short-circuit would not be a serious matter. It is true that the primary of the regulator would have to be cleared, but as this represents only a fraction of the feeder load, and as the regulator has considerable impedance, the momentary disturbance to the system would be small. The author gives the full-load losses as 4 per cent in a large, and 8 per cent in a small, induction regulator. The corresponding figures for a tap-switch booster would be 1½ per cent and 3 per cent, but it must be admitted that the latter device will not do all that an induction regulator will do. For a motor-driven boosting alternator one would expect these losses to be 12 per cent and 24 per cent. Many members will have seen d.c. power stations equipped with small motor-driven feeder boosters in which the losses are more than 30 per cent.

Mr. C. Turnbull: In our own area we have a bulk supply through long feeders, and there is a tendency for the pressure to fall during the times of heavy load, and for it to rise excessively on light load. We have recently installed a booster and are able to give consumers a good pressure on the peak loads and to reduce the pressure in the middle of the night, which greatly improves the life of street lamps, and also reduces the number of lamp failures. In ordering a booster, the natural tendency is to arrange it to boost upwards, but in some circumstances it may be found better to set the pressure high by means of the transformer tappings, and to boost downwards at times of light load. This will give the booster less work to do. In many cases a good arrangement is to arrange the transformer tappings so that the booster has a minimum of work to do, only boosting up when the load is heavy, and boosting down when the load is light, but in times of normal load doing little or no work.

Mr. L. H. A. Carr (*in reply*): The practice in this country with regard to boosting transformers and induction regulators has not yet become crystallized, since the need for such forms of apparatus is only in its infancy. This need is, however, growing, and it was largely to explore the position from the point of view of the induction regulator that this paper was written, rather than to lay down a hard and fast rule of "standard practice." At the same time, one cannot at all agree with most of Mr. Bass's contentions. Where steps of 5 per cent in voltage are sufficiently fine, the

boosting transformer is probably—one might almost say certainly—the better alternative; but it has yet to be proved, first, that steps as coarse as this can be used in the majority of cases, and secondly that where smaller steppings are necessary (taking into consideration first cost, reliability, and cost of maintenance) the boosting transformer is the better scheme. Further, I cannot agree with Mr. Bass (and neither apparently does Mr. Crompton) that the gradual-control feature of the induction regulator is "not of great practical importance."

With very small installations the relative figures of cost quoted by Mr. Bass are probably correct, but the larger the output required, the cheaper becomes the induction regulator compared with the transformer-step-switch combination. Further, as the permissible stepping limit becomes smaller, so the cost and complication of the boosting transformer combination increases, as must also its liability to breakdown, while the necessity for continuity of supply during switching operations still further increases the cost of this system. It is therefore found in some of the larger projected installations that the induction regulator costs little more than the transformer scheme, while having the advantage of possessing fewer links in the chain and hence less liability to break down.

Mr. Crompton suggests that the reliability of the automatic control gear may not be so high as that of the regulator itself, and that a breakdown may occur due to this. None of the power, however, goes through the control gear, and as hand operation is always provided as a stand-by, the breakdown of the control gear does not necessitate putting the regulator out of action.

Mr. Bass suggests the use of a step-switch transformer together with a small induction regulator to bridge the gaps. This is quite feasible, but except in a large installation the first cost of such a scheme would be relatively high, as it must be remembered that the cost per kilovolt-ampere of a regulator falls rapidly as the size is increased, so that, conversely, if the size of the regulator is decreased the cost per kilovolt-ampere (of the regulator) increases rapidly, and little saving is made in the cost of the regulator if the latter falls below a certain critical size for each voltage. For large installations, however, the scheme is worth consideration, which as a matter of fact it has received in certain specific cases.

With regard to the cancellation of the negative boost, it would be possible to place half the secondary winding on the primary member, and so produce a boost varying from zero in one direction only. While I believe this has occasionally been done in the case of a single-phase induction regulator used for testing purposes, the construction is of no advantage in the feeder regulator and there is no saving obtained by adopting it. The losses would remain the same, and the only result (besides an infinitesimal lowering of the leakage reactance) would be the production of a regulator to give from 0 to, say, + 10 per cent boost, instead of − 10 per cent to + 10 per cent, at the same cost and with the same losses. In a large installation, where a smaller regulator could be built economically, instead of the above scheme it would be wiser to consider a + 5 per cent boosting transformer permanently in circuit, together with a ±5 per cent regulator. The alleged uselessness of the negative boost has, however, been over-stressed in the discussion. The question does not arise in the case of complete new installations where the transformers can be made of a suitable ratio, and even when the regulator is added to an existing transformer distribution system the transformer voltage may frequently be adjusted, since the majority of large transformers appear to be provided with taps covering from − 5 per cent to + 5 per cent. Further, in an interconnector between two power stations both positive and negative boost are required, so that the boost may be set to correspond with the power flow.

I can assure Mr. Bass that induction regulators for feeders are most certainly designed to withstand the very large stresses that may occur on short-circuit, special attention being paid to the bracing of the end windings, strength of gears, etc.

I regret that I have no particulars available of single-phase three-wire regulators. Such a regulator is, however, perfectly feasible, and would have two secondary windings on the same core, a single primary winding being connected across the outers. So long as the out-of-balance current is small, this arrangement would work quite satisfactorily. The advantage of this scheme is that it would be cheaper, and slightly more efficient than two single-phase regulators each of half the capacity. For operating a single-phase regulator, in order to overcome the difficulty of the limited starting torque of the single-phase induction motor, at least three alternative schemes may be employed:—

(1) The motor is allowed to run continuously, clutches or ratchets being operated automatically when a change of boost is required.

(2) The motor is geared down to the regulator through a low-speed crank and connecting rod operating a ratchet device. The gear is so devised that the motor always starts with the pawls of the ratchet out of engagement, and thus starts light.

(3) The motor drives the regulator through a centrifugal slipping clutch.

In reply to Mr. Crompton, the boost given for a certain relative position of stator and rotor depends, for all practical purposes, solely on that position. The only effect of the power factor of the load is to change the vector relationship of the internal impedance drop of the regulator, the effect of which change is practically imperceptible at the terminals. It is, therefore, possible to mark the regulator so that definite settings correspond to certain definite amounts of boost. Finally, I would state that the kVA figures quoted refer to the output of the regulator and not to the capacity of the feeder to which it is connected.

POLYPHASE TRANSFORMER MAGNETIZING-CURRENT WAVE-FORMS.*

By P. KEMP, M.Sc.Tech., Member, and H. P. YOUNG, Associate Member.

(*Paper first received 27th January, and in final form 22nd April, 1925.*)

SUMMARY.

The paper deals with the analyses of the magnetizing currents taken by groups of transformers connected in various manners for operating on polyphase (and particularly on three-phase) systems. The method of treatment employed is to assume that a sine wave of flux necessitates the application of a peaked wave of magnetizing current, and that the difference between this desired wave and the wave actually obtained brings about various modifications in the behaviour of the apparatus. The properties of the star, delta, tee- and vee-connected windings are discussed, particularly with reference to harmonics, oscillographic confirmation being given where possible. Various six-phase systems are also discussed, in view of their importance in connection with rotary-converter work.

For convenience, a number of oscillograms have been omitted, only the results being quoted in the paper itself.

It is a well-known fact that third-harmonic currents cannot flow in a balanced three-phase star-connected system with isolated neutrals, and that a three-phase delta constitutes a short-circuit path for such currents. Furthermore, the magnetizing current flowing through a winding surrounding an iron core contains a very considerable third harmonic if the iron is saturated, assuming the applied E.M.F. to be sinusoidal in wave-form. If, therefore, three such magnetizing windings be connected in star and a sinusoidal E.M.F. be applied to the combination, the flux densities in the cores being sufficient to cause saturation, it follows that since the third-harmonic currents cannot flow directly, the form of the M.M.F. and the resulting flux waves must be modified in some way.

The object of the present investigation is to examine certain aspects of this subject and to trace out the mechanism whereby the various results are obtained. For this purpose a method of treatment will be employed which involves the idea of considering a sine wave as being composed of a peaked component consisting of a sine wave and a third harmonic, together with a third-harmonic sine component equal and opposite to the third-harmonic part of the main peaked component. This idea is illustrated in Fig. 1, which shows a resultant sine curve A, and its two equivalent components, B and C, these being the peaked and third-harmonic components respectively. As ordinary transformer magnetizing currents can be represented to a fair degree of accuracy by a sine wave together with a third harmonic, and very accurately by a sine wave together with a third and fifth harmonic, the applied E.M.F. being sinusoidal, the main peaked component, B, can be made to represent the main fundamental magnetizing current, whilst the third-harmonic component, C, will be employed in producing a third-harmonic flux. The treatment could be carried further, if desired, by considering the third harmonic itself as being peaked, the difference between the peaked and the sinusoidal third harmonic giving rise to a further magnetizing current of nine times the fundamental frequency.

In the case of a balanced three-phase star-connected choking coil supplied with a sinusoidal line voltage, the neutral points being isolated, third-harmonic currents cannot circulate. Since, however, a sinusoidal phase voltage demands a magnetizing current containing a third harmonic, it follows that the phase voltage is not sinusoidal. The difference between the actual phase-voltage wave-form and the sine phase-voltage wave-

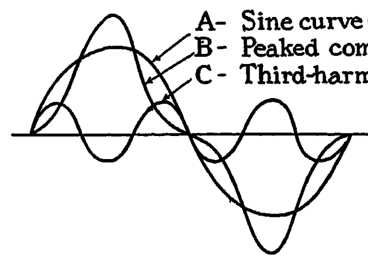

FIG. 1.—Composition of sine curve.

form, obtained from a consideration of the line voltage, must be exactly neutralized by a corresponding difference in the other phase. This difference consists of a third-harmonic voltage; for since the fundamental E.M.F.'s directed away from the neutral point are 120° out of phase, the third-harmonic voltages are 360° out of phase and so cancel out between lines. (Higher harmonics such as the ninth, etc., are here neglected.)

If the line potentials are symmetrical with respect to earth, the potential of the neutral star-point will not be that of earth, but will oscillate about earth potential at third-harmonic frequency with a magnitude equal to that of the third-harmonic phase voltage. If the choking coil neutral point is in electrical connection with the supply neutral point, these third-harmonic voltages will be expended in forcing third-harmonic currents through the system, the fourth wire acting as a drain since it forms the return path of all three third-harmonic currents. The relative magnitudes of the impedance of the fourth wire and the phase windings will now determine the proportion of the third-harmonic voltages which is absorbed in the windings themselves. The

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oscillation of the neutral potential is reduced and, if the return path constitutes a short-circuit, the neutral potential is practically stabilized at earth potential, the oscillation being damped out.

In the case of the delta-connected choking coil, a sinusoidal line voltage will bring about phase currents which contain a third harmonic. The fundamental components of these currents will flow in the line conductors, but the third-harmonic components will all be in phase with each other, and so will circulate around the delta, which constitutes a short-circuit to them. The third-harmonic currents thus do not appear in the lines, and the third-harmonic voltages are suppressed.

It is interesting to consider the mechanism whereby a generator giving a pure sine wave of voltage, not only between lines but also between each line and the star point, can supply the primary phases of a three-phase choking coil or a transformer with the necessary third-harmonic magnetizing current of whatever amplitude may be demanded. The condition will be simply but adequately represented by the case of a single-phase generator developing a pure sine wave of E.M.F. directly connected to a choking coil. Neglecting all losses in

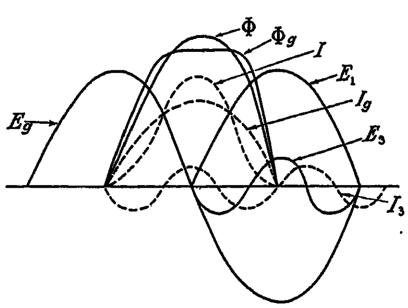


FIG. 2.—Production of third harmonic in current wave of choking coil.

the latter, the mechanism is explained by the waves shown in Fig. 2.

The generator voltage, E_g, sets up a sinusoidal magnetizing current, I_g, lagging by 90°, and this gives rise to a flat-topped flux wave, Φ_g. This in turn induces a reactive E.M.F. which can be obtained by the differentiation of the flux wave. This reactive E.M.F. will consist of a fundamental component, E_1, which is balanced by the applied generator voltage, and a third-harmonic component, E_3, which is free to circulate a third-harmonic current, I_3, through the circuit. This current, lagging by its appropriate angle behind the voltage E_3, can now be combined with I_g to give the resultant magnetizing current, I. In addition, however, it sets up a harmonic flux in phase with itself, and this, combined with the flux directly due to the applied voltage, brings about the resultant flux wave, Φ. This wave is still flat-topped to a certain extent, but not so much as is the wave represented by Φ_g.

It will be noticed that the generator only supplies directly the fundamental magnetizing current and the current necessary to account for the various losses. This is true whether the star points of the generator and choking coil are isolated or directly connected together. The choking coil supplies the harmonic currents necessary for its own magnetization, the generator windings merely forming part of the path for the circulating currents. If, owing to the method of connection, there is no path for third-harmonic currents, the flux wave will suffer a further deformation, and this will cause the choking coil to set up additional fifth harmonics, etc., which will tend to make up the deficiency as completely as it is able.

The effects of one harmonic can only be imitated exactly by a combination of an infinite number of other harmonics, all of equal amplitude to one another and to that of the harmonic whose effects are to be reproduced. This can be seen from a consideration of the expression :—

$$E_1 \sin \omega t + E_3 \sin 3\omega t + E_5 \sin 5\omega t + \ldots = 0$$

Putting $E_1 = E_3 = E_5$, etc., this resolves itself into

$$\sin \omega t + \sin 3\omega t + \sin 5\omega t + \ldots = 0$$

and hence

$$\sin 3\omega t = - \sin \omega t - \sin 5\omega t \ldots$$

As this is not a convergent series, the effect of a dozen or so of terms does not give a useful approximation to the desired harmonic.

Indeed, since the various terms all commence in phase with one another, the initial part of the wave will be widely dissimilar from that desired. The central portion, however, corresponding to the period of saturation, will approximate fairly closely because neighbouring harmonics are on alternate sides of the zero line. The maximum value of the desired harmonic wave will be faithfully reproduced if an odd number of components be chosen.

The above ideas will be expanded so as to deal with various transformer connections, the applied E.M.F.'s being assumed to be sinusoidal in all cases.

CASE 1: STAR-STAR CONNECTION.

(*a*) *Both neutrals isolated.*—Assuming a balanced system, the third-harmonic currents cannot circulate, so that as a first approximation the magnetizing current may be considered as obeying the simple sine law. To produce a sine wave of flux, however, necessitates a magnetizing current having a third harmonic, owing to the shape of the *BH* curve, the magnitude of this third harmonic depending upon the degree of saturation. The effect of hysteresis is here neglected but will be considered later. The actual sine wave of magnetizing current may be considered as consisting of a peaked component, itself consisting of a pure sine wave together with a third harmonic, and a third-harmonic component to balance the corresponding third harmonic in the main component (see Fig. 3). The peaked component of the magnetizing current will give rise to a sine wave of flux, and the third-harmonic component may be assumed to give rise to a third-harmonic flux. (This is not strictly accurate, as the harmonic M.M.F. cannot produce the same effect as it would do if the fundamental M.M.F. were absent. The degree of saturation will affect the discrepancy.) The resultant flux wave will be flat-topped or dimpled, depending upon the degree of saturation. Both component fluxes will induce

E.M.F.'s in the primary and secondary, the wave-forms being the same in the two cases. These E.M.F.'s will lag behind their respective fluxes by 90°. The resultant wave of induced E.M.F. will thus be peaked and the harmonics set up by the transformer, which are not balanced by corresponding generator harmonics, are expended in impedance drops. The phase voltage between line and star point is thus seen to contain a considerable third harmonic. The R.M.S. value of the potential of the star point will differ considerably from that of earth, assuming the three-phase system to be balanced about earth potential. The voltage between star point and earth will produce a triple-frequency effect, its magnitude depending upon the degree of saturation in the coils.

It is found, however, that with the iron used in practice the effect is not so simple as indicated above, for the fifth harmonic is by no means negligible. The manner in which the fifth harmonic is set up will next be discussed. It was stated above that a sine wave of magnetizing current could be split up into two components, one producing a flux wave of fundamental frequency and the other one of third-harmonic frequency. The addition of two waves in this manner is true for M.M.F.'s, but is only correct for fluxes throughout the straight-line portion of the *BH* curve. When saturation commences to take place, the resultant flux due to two M.M.F.'s acting simultaneously is less than the sum of the fluxes set up by them when acting independently.

In considering the effect of a third harmonic upon a sine wave of flux, it follows that the half wave of

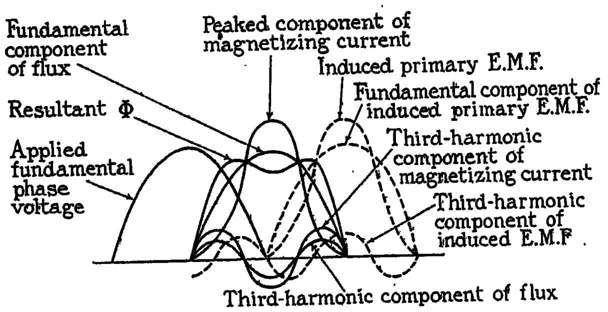


FIG. 3.—Origin of peaked phase voltage in star-connected system.

harmonic flux occurring in the middle of the fundamental half wave will have a smaller amplitude than the half waves immediately preceding and following it. This is indicated in Fig. 4 (*a*), which shows a fundamental half wave together with a third harmonic, the middle half wave of which is damped down. Fig. 4 (*b*) shows a similar effect, but in this case the distortion is due to a combination of third and fifth harmonics. The two resultants are very similar. This goes to show that owing to the gradual bending over of the *BH* curve, a fifth harmonic is introduced into the flux wave in addition to the third already described. The fundamental, third and fifth harmonics are all in phase with one another, i.e. they all commence to rise from zero in the positive direction simultaneously.

Owing to the presence of a fifth harmonic in the flux wave there will be a fifth-harmonic E.M.F. induced in each phase winding. These E.M.F.'s will not cancel out between lines as in the case of the third harmonic, but will give rise to a line resultant, causing a fifth-harmonic magnetizing current to circulate between transformer and generator, and there will be a fifth harmonic in the P.D. between transformer line terminals, even though the open-circuit induced E.M.F. in the generator be an ideal sine wave. The transformer phase-voltage can be obtained by the differentiation of the flux wave. This voltage wave, together with its components, corresponding to the flux wave shown in Fig. 4 (*b*), is represented in Fig. 4 (*c*). It will be observed that, whilst the generator supplies the fundamental magnetizing current directly, the transformer iron is

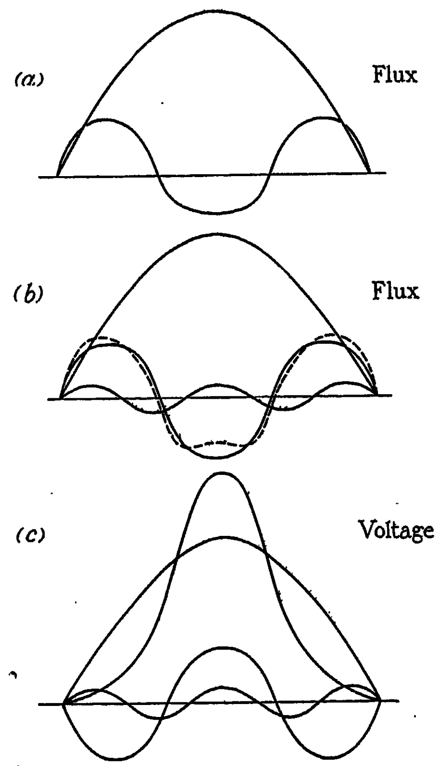


FIG. 4.—Origin of fifth harmonic.

responsible for the setting up of the voltage harmonics and hence the harmonic components of the magnetizing current. The third harmonic is absent in the magnetizing-current wave, but instead of this there is a pronounced fifth harmonic.

The phase of the fifth harmonic in the magnetizing current can be obtained from Fig. 4 (*b*). Since the fifth-harmonic flux is tending to peak the resultant flux wave, the fifth harmonic in the magnetizing current must do the same. This harmonic cannot, however, make up for the lack of third harmonic, and so the resultant flux wave is still flat-topped. The distortion of the flux wave is much less than the distortion of the corresponding voltage wave, but it can be seen quite distinctly in the oscillograms shown in Fig. 5. The flat-topped wave represents the flux wave of a group of three single-phase transformers with the neutral isolated,

the other wave representing the condition when the transformer star point was connected to the generator star point. This permitted the third-harmonic magne-

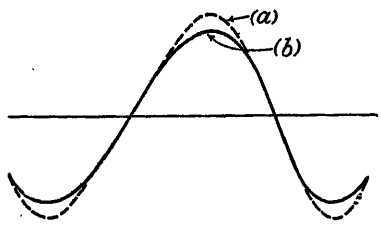
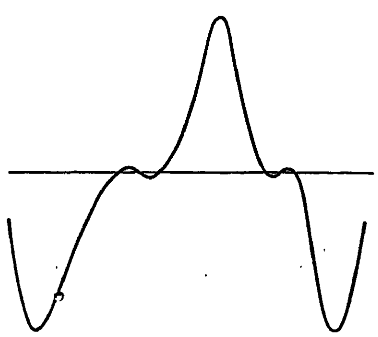


FIG. 5.—Flux waves with star points; (a) connected, (b) isolated.

tizing current to flow and so enabled the flux wave to regain approximately its sinusoidal shape. The phase voltage of the same group of transformers when operating with an isolated neutral is given in Fig. 6. This voltage wave contains a 46 per cent third and a 10 per cent fifth harmonic, the former approximately in opposition and the latter in phase, so that they both tend to peak the resulting wave.

If a sine wave of terminal volts between lines be assumed, there may be a third harmonic in the phases (i.e. between line and neutral) but there cannot be any fifth harmonic, since if there were it would appear



$$e = 100 \sin \omega t + 46 \sin (3\omega t + 174^\circ) + 10 \sin (5\omega t + 320^\circ)$$

FIG. 6.—Phase voltage with isolated neutral.

between lines. In order to comply with this condition a very considerable fifth harmonic is set up in the primary magnetizing current, this being of sufficient magnitude to cause a pronounced dimple in the flux wave and hence in the current wave when the flux density is high. Fig. 7 shows an example of this and refers to ordinary stalloy plates in which the maximum flux density is 14 000 lines per cm². The flux wave contains an 18·4 per cent third harmonic, giving rise to an appreciable dimpling, whilst the fifth harmonic in the magnetizing current rises to the high value of 23·2 per cent. The phase voltage is thus seen to contain a third harmonic having a magnitude equal to 55·2 per cent of the fundamental voltage between line and neutral. The corresponding values for other flux densities are shown in Table 1.

The change in the phase of the fifth-harmonic magnetizing current is clearly shown in the table, and the figures seem to point to the fact that the third-harmonic phase voltage reaches an upper limit of the order of 60 per cent of the fundamental (see Fig. 8).

Considering next the effect of hysteresis, it will be assumed that a current of one frequency cannot be produced by an E.M.F. of another frequency. In the usual method of treatment this condition is not adhered to, and a hysteresis current of irregular wave-form is obtained as a result. This gives rise to a discrepancy which is commonly neglected, for if the applied E.M.F. is sinusoidal, the power factor of the hysteresis current of irregular wave-form cannot be unity, and, apart from an E.M.F. of one frequency producing a current of

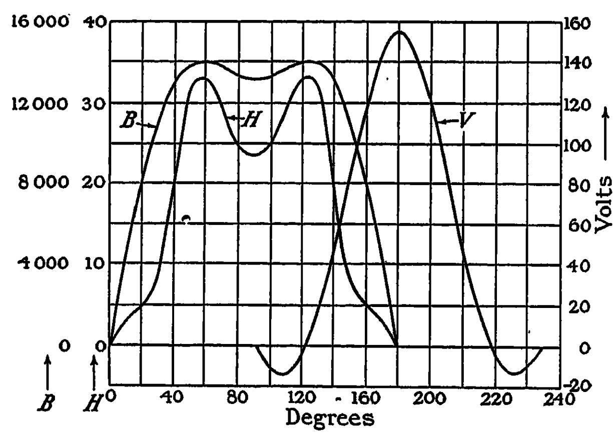


FIG. 7.—Fifth harmonic in magnetizing current with high flux densities.

another frequency, it is supposed to produce a current which cannot give rise to any watts. The current is therefore not solely a hysteresis current.

It is much simpler to assume that the applied voltage produces a sine wave of current of sufficient magnitude to account for the hysteresis loss, since this is supplied directly from the generator or other source of power.

TABLE 1.

Stalloy Plates.

Max. flux density in lines per cm²	11 000	12 000	13 000	14 000
Fundamental *H*	7·94	12·28	19·68	30·21
Fifth-harmonic *H*	+0·27	−0·56	−3·37	−7·02
Third-harmonic phase voltage	16·8 %	42·6 %	51·9 %	55·2 %
Third-harmonic flux	5·6 %	14·2 %	17·3 %	18·4 %
Fifth-harmonic magnetizing current	+3·4 %	−4·6 %	−17·1 %	−23·2 %

Subtracting this current from the total no-load current, the total magnetizing current is obtained. This now consists of a fundamental and harmonics symmetrically distributed about a 90° vertical axis, together with components more or less in phase with the voltage, tending to increase the resultant current in the first quadrant and to diminish it in the second. The result is to elevate the customary hump on the left-hand side of the wave and to depress the one on the right.

The fundamental component of this magnetizing current is supplied by the generator. This induces a flat-topped flux wave which, owing to the harmonics contained in it, sets up E.M.F.'s of various frequencies. These E.M.F.'s give rise to the various harmonics in the resultant magnetizing current and tend to eliminate the flux harmonics, reducing the distortion of the flux

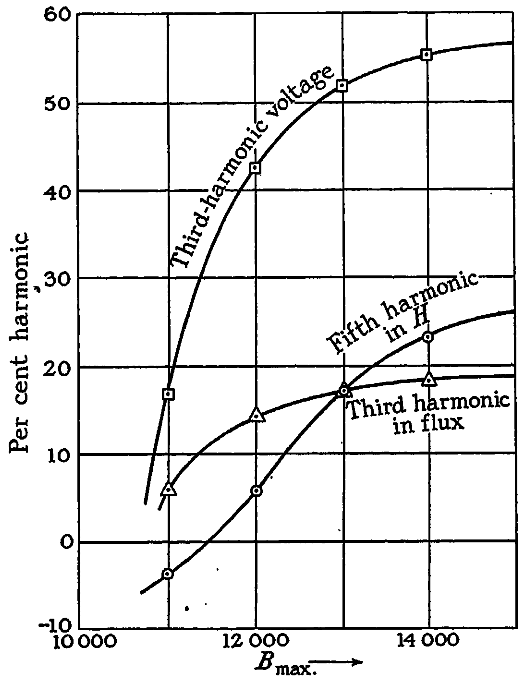


FIG. 8.—Summary of harmonics for various values of B_{max}.

wave. If no hysteresis were present, these harmonics would all be symmetrical about the 90° ordinate, but owing to the fact that the "up" magnetization curve differs from the "down" curve, some of the harmonics have a phase displacement and cause part of the familiar dissymmetry in the resultant current wave. Nevertheless, these components of the current strictly belong to the magnetizing and not to the loss portion of the current, and are derived not from the generator directly but from the transformer itself. The generator supplies only the fundamental sine wave of magnetizing current and a power component, also sinusoidal and of fundamental frequency, to account for the hysteresis loss. All harmonic currents are derived from the transformer, the shape of the flux wave so adjusting itself that these components are possible.

If the impedance of the paths of the harmonic currents were negligibly small, the number of harmonics in the current wave would be infinite and the flux wave would be approximately sine-shaped. But in the case of transformers or choking coils this condition is impossible of attainment since the reactance is directly proportional to the frequency. Again, in the case of a three-phase star-connected bank with an isolated neutral the third harmonic and multiples thereof cannot act, and the deficiency due to this cause cannot, as previously shown, be made up by the higher harmonics. As a consequence the flux wave can never be exactly sine-shaped, although a very close approximation may be obtained with favourable conditions.

In a single-phase transformer or choking coil, third-harmonic currents are possible and such currents are supplied by the transformer itself on account of its particular flux wave-forms. In the case of a balanced three-phase star-connected group with isolated neutral, these third-harmonic currents cannot flow, and hence the flux waves must adjust themselves in shape to meet the new conditions. Generally, this means flatter-topped flux waves. If the maximum flux density in the magnetic cores is the same as before, the hysteresis loss per unit volume will be the same, assuming the same frequency, and so the hysteresis current should be the same. On the usually accepted method of determining hysteresis current, this would work out differently in view of the different shape of the flux wave, and this is surely wrong. This again serves to point out that the generator supplies the sinusoidal hysteresis current, and the flux waves give rise to induced E.M.F.'s which contain harmonics and so cause the potential of the neutral to oscillate. The magnetizing currents, deficient in third harmonics, are partly obtained from the generator (fundamental) and partly from the transformer (harmonics).

(*b*) *Both neutrals isolated. Secondary delivering four-wire supply.*—It is well known that an unbalanced load to the neutral cannot be delivered satisfactorily with this combination, since the corresponding primary currents which magnetize the core, result in a serious shifting of the primary neutral point. The maintenance of the voltage on the secondary side is therefore impracticable. If, however, the primary neutral be connected to the star point of the generator windings, the unbalanced current can circulate between the primary winding and the corresponding phase of the generator winding, the phase voltages being therefore approximately balanced. These considerations apply particularly to single-phase transformers, both core and shell type, and to three-phase shell-type transformers. They only apply to a limited extent to three-phase core-type transformers, since in this case the magnetic fluxes in the three cores are interlinked, giving a very much better balance of the phase voltages.

If the secondary supplies a balanced load, however, there is a closed path for the third-harmonic components of magnetizing currents, these currents circulating through the transformer windings, lines and load impedances. As all the third-harmonic currents are in phase with one another, their arithmetical sum will return to the star point of the transformer coils via the fourth conductor.

The mechanism by which the third-harmonic magne-

tizing current is referred to the secondary may here be mentioned. Since the primary neutral is isolated, the primary magnetizing current cannot contain the necessary third harmonic and so can be represented by a peaked wave producing a sine wave of flux, together with a third-harmonic component in phase, this producing a third-harmonic component of flux. The question of saturation in the case of the harmonic is here neglected. The two component current waves form a resultant sine wave, and the two component flux waves form a resultant flat-topped flux wave. Actually the resultant magnetizing current will contain also a considerable fifth

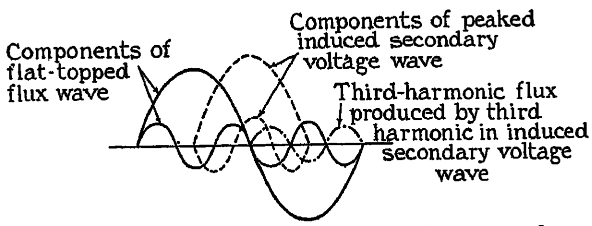


FIG. 9.—Harmonic magnetization of core from secondary.

harmonic, but that is not material to the present argument. The component flux waves may each be regarded as giving rise to independent reactive E.M.F.'s in the primary windings and to induced E.M.F.'s in the secondary windings. The sine components of the latter will circulate the load currents, the vector sum of which equates to zero, so that they do not appear in the fourth wire. The third-harmonic components of the E.M.F.'s will circulate third-harmonic currents which, being in phase, will return to the transformer secondary neutral point by way of the fourth wire. The current in this

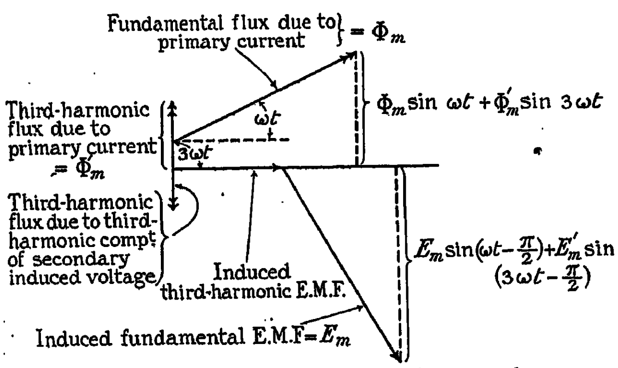


FIG. 10.—Vector diagram illustrating secondary magnetization.

wire will be the arithmetical sum of the three third harmonics. The latter will, neglecting losses, provide secondary ampere-turns which can magnetize the core, and the resulting third-harmonic flux will lag by 90° behind the voltage producing it. A reference to Fig. 9 shows that this flux tends to neutralize the third-harmonic component of flux set up by the primary ampere-turns. The hypothetical third-harmonic flux set up by the third harmonic in the induced secondary voltage wave nearly neutralizes the hypothetical third-harmonic flux produced by the primary ampere-turns. In consequence, the flux set up by the primary magnetizing current will be much more nearly sinusoidal than before, and the induced E.M.F.'s will also be approximately sinusoidal. The peak of the phase voltages will be reduced and the

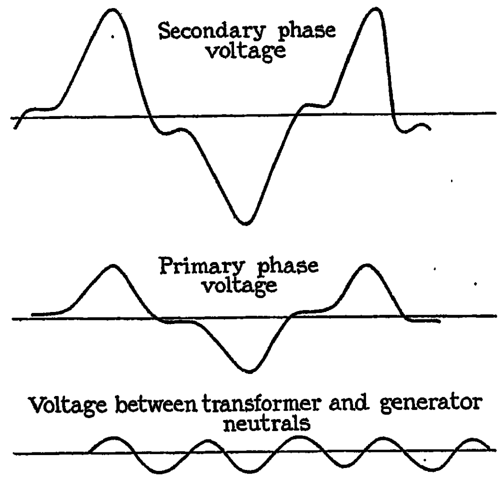


FIG. 11.—Oscillograms of star-star-connected transformers with isolated neutrals, delivering balanced 4-wire load (0·4 A).

oscillation of the primary neutral point will be largely damped down.

An alternative method of viewing the problem is by

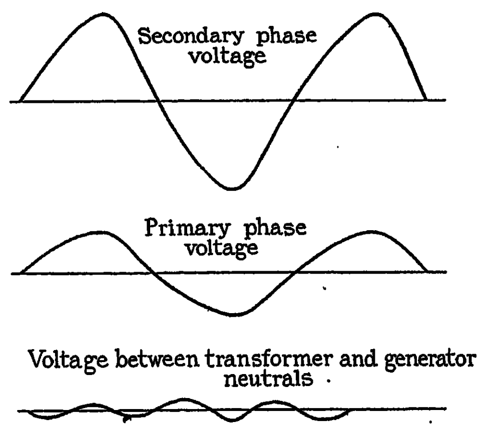


FIG. 11 (*a*).—Oscillograms of star-star-connected transformers with isolated neutrals, delivering balanced 4-wire load (1·5 A).

the aid of a vector diagram, as shown in Fig. 10. The various vectors in this diagram correspond exactly to the various curves shown in Fig. 9.

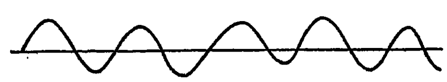


FIG. 11 (*b*).—Wave-form of voltage between transformer primary and generator neutral points. Transformer secondaries on open circuit.

It is, however, noteworthy that the primary flux wave, the primary reactive E.M.F., and the induced secondary E.M.F., cannot be entirely free from third harmonics, since these must be of sufficient value to

circulate the third-harmonic magnetizing current in the four-wire secondary circuits. It should also be noted that the magnitude of the third-harmonic magnetizing current circulating in the secondaries is inversely proportional to the impedances of the secondary circuits. Thus at no load the secondary induced E.M.F.'s, the primary reactive E.M.F. and the resultant flux in the core will all have maximum third-harmonic components, these decreasing as the load is increased, being absorbed in circulating the third-harmonic magnetizing currents through the secondary circuits. It is thus seen that in the case under consideration the voltage wave-forms are dependent upon the secondary load.

Figs. 11, 11 (*a*) and 11 (*b*) show a series of oscillograms taken on a group of three 2-kVA single-phase trans-

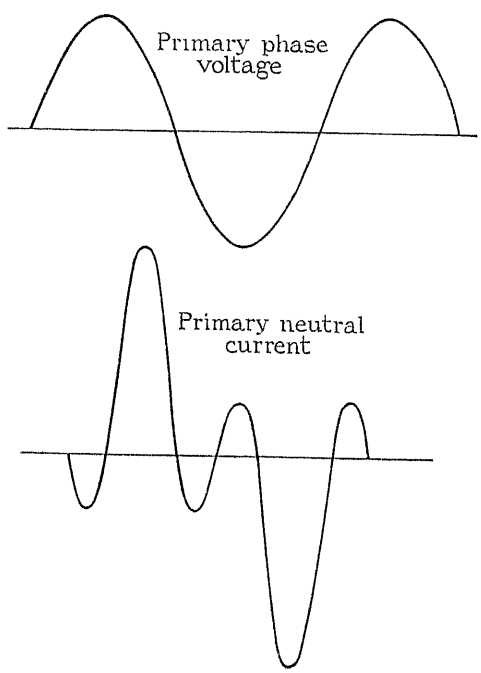


FIG. 12.—Oscillograms of star-star-connected transformer with primary and generator neutrals connected. Neutral current (R.M.S.) 1·82 A.

formers, both neutrals being isolated, and the secondary delivering a balanced four-wire supply. The supply pressure was practically sinusoidal. The full-load secondary current was 10 amperes, but even with a load of 1·5 amperes the harmonics in the waves had been largely damped down as shown in Fig. 11 (*a*). As the load is gradually decreased beyond this point, the harmonics in both primary and secondary phase voltages gradually increase, as does also the potential oscillation of the primary neutral, this being measured with respect to the generator neutral which is assumed to be stable. The oscillation reaches its maximum amplitude when the load is reduced to zero, as shown in Fig. 11 (*b*).

(*c*) *Primary neutral earthed.*—The effects of earthing the primary neutral at the transformer, the generator windings being insulated, is practically the same as earthing the generator neutral and keeping the transformer neutral insulated. The potentials of the various windings are tied to earth, but no third-harmonic magnetizing currents can flow. The effects are similar to those dealt with in Case 1 [(*a*) and (*b*)].

Where the transformer neutral is earthed on the system in which the generator neutral is earthed as well, however, different conditions are set up. There is

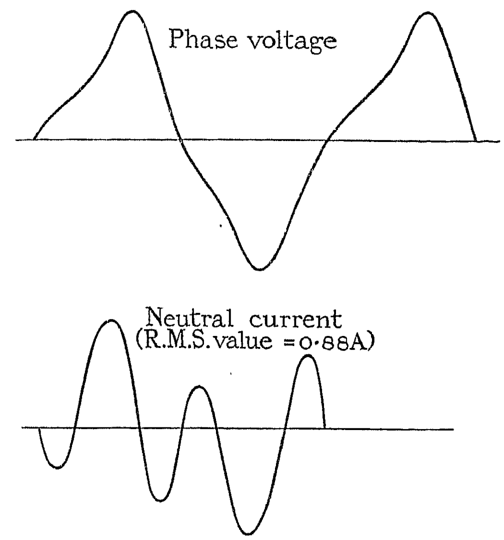


FIG. 12 (*a*).—Oscillograms of star-star-connected transformers with primary and generator neutrals connected. Neutral current (R.M.S.) 0·88 A.

now a closed path for the third-harmonic magnetizing currents to flow in the primary system. The magnitudes of these currents will depend to a considerable extent upon whether the windings are earthed solidly or through resistances. In the latter event they will be limited in value to an amount depending upon the value of the

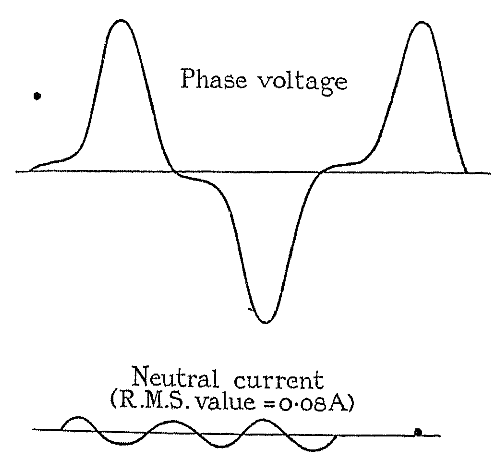


FIG. 12 (*b*).—Oscillograms of star-star-connected transformers with primary and generator neutrals connected.

earthing resistances. The triple-frequency oscillation of the neutral potential is very much reduced and may be brought down to a negligible value if the earthing device is of sufficiently low resistance. The advantage thus gained, however, may be more than counterbalanced in certain cases by the third-harmonic magnetiz-

ing currents setting up resonance on account of the line capacity. In many cases, therefore, this connection is dangerous and should be avoided.

A series of oscillograms is shown in Figs. 12, 12 (*a*), 12 (*b*) and 12 (*c*), illustrating the effect of connecting the generator and transformer primary neutrals together through resistances of various magnitudes. The transformers were the same as those used for Fig. 11, and were connected star-star, the supply pressure being again practically sinusoidal. The resistance in the primary neutral wire was varied between a minimum value and infinity, and the oscillograms refer to (*a*) primary phase voltage and (*b*) neutral-wire current. The fundamental component in the neutral current was due to lack of balance on the part of the individual transformers. This current at fundamental frequency was gradually eliminated as the resistance in the neutral wire was increased. The amplitude of the neutral third-harmonic current was gradually reduced simultaneously, but not to the same extent. The third

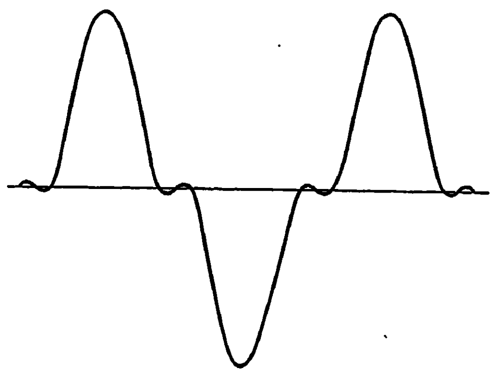


FIG. 12 (*c*).—Oscillogram of phase voltage. Neutral current zero.

harmonic in the phase voltage gradually increased as the resistance was increased, and became a maximum when the neutral wire was open-circuited. The ninth harmonic in the current is negligible in the present instance.

The effect of line capacity should also be considered; this is referred to in Case 6 (*c*).

CASE 2: STAR-STAR-TERTIARY DELTA CONNECTION.

Primary and secondary neutrals isolated.—When the ordinary star-star connection is applied to a three-phase shell-type or three single-phase shell- or core-type transformers, considerable third-harmonic voltages are induced in the windings due to the suppression of the third-harmonic magnetizing current in the two windings. These voltages may be of the order of 50 per cent of the fundamental at ordinary core flux densities, and may even become as high as 60 per cent in extreme cases (see Fig. 8).

The addition of the tertiary winding may be adopted for one or more of the following reasons:—

(1) To protect the transformer from excessive third-harmonic potentials.

(2) To stabilize the neutral potential.

(3) To prevent telephone interference in the lines and earth.

(4) To supply a load in addition to any of the above purposes, i.e. a condenser load for power factor improvement.

When used for the first-named purpose, the primary and tertiary windings act, from the point of view of magnetization, as a star-delta system (dealt with in Case 4). The flux wave will have a slight tendency towards being flat-topped, thus giving rise to slightly peaked voltages in both secondary and tertiary windings. In the latter case the fundamentals neutralize one another around the closed delta, but the third-harmonic components are virtually on short-circuit. The resulting third-harmonic currents will tend to supply the deficiency in the primary magnetizing current and will restore the flux wave almost to its normal shape. It is, of course, impossible that it should do this completely, as in this event there would be no harmonic E.M.F. generated in the tertiary, and the action would cease. The tertiary winding is designed to carry only the third-harmonic magnetizing currents (together with the ninth, etc.), and low leakage reactances of the primary and tertiary windings considered in combination are not essential. In fact it is desirable that these reactances should be high enough to limit to a safe value the circulating current produced in the tertiary by an accidental "line to neutral" short-circuit. In this event the voltage in one leg of the delta disappears, and the remaining two phases may set up a resultant voltage, acting round the closed tertiary circuit, sufficient to burn it out by means of current at fundamental frequency.

When a tertiary winding is employed for the purpose of stabilizing the potential of an oscillating neutral a different set of characteristics is desired. The oscillation of the secondary neutral potential is due to the presence of third-harmonic E.M.F.'s in the secondary phases, and these in their turn are due to the flattening of the flux wave. It is therefore desirable that the latter should be reduced to the smallest possible amount. The third-harmonic component of the magnetizing current, which is derived from the tertiary winding, should be set up with the least possible magnetic leakage, and the coupling between the primary and tertiary should be close. In this manner the deformation of the flux wave necessary to set up the required E.M.F. in the tertiary can be reduced to a minimum.

Telephone disturbances are due to harmonic currents circulating in lines or earth paths which run parallel to the telephone cables. In this connection the ninth harmonic may not be neglected. The interference is dependent upon the magnitude of the current and the length of the interfering line, and is only likely to take place on long transmissions when operating either with a fourth wire or with an earthed neutral, or, in other words, where there is a low-impedance path for the harmonic currents.

When a tertiary winding is used to supply load it practically devolves into an additional secondary, and the turns must be of sufficient cross-section to carry their own load currents at fundamental frequency, in addition to the magnetizing currents at harmonic frequency. In this connection a condenser load has

been suggested for the purpose of phase-advancing. From the point of view of protection from breakdown a looser coupling is now desired, with respect to both the primary and the secondary, so as to provide sufficient leakage reactance to withstand either a short-circuit on its own lines or on those of other windings. In any case a loose coupling is desired with respect to the secondary. The tertiary winding may be incorporated in the secondary by opening the neutral point of the latter and connecting the resulting three free ends to the three junctions of the auxiliary delta as shown in Fig. 13. In this way a saving in secondary copper may be brought about, since the third winding is usefully employed in carrying the secondary load current and in providing a portion of the secondary E.M.F., in addition to its other functions. The method suffers, however, from two disadvantages. There is no point available for direct earthing should the occasion arise, and there is a small phase displacement of the secondary line E.M.F.'s so that a transformer connected on this plan would not be capable of being paralleled directly with another one unless the angle of phase displacement were the same. This angle depends upon the relative number of turns per winding in the main secondary

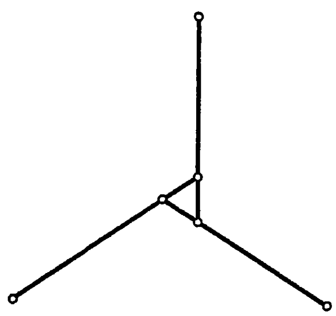


FIG. 13.—Interconnected tertiary winding.

and auxiliary delta windings, and lies between the extreme limits of 0° and 30°.

When the primary or secondary is connected in delta there appears to be no adequate reason for the introduction of a tertiary delta.

Oscillograms illustrating the effects of a tertiary delta are shown in Fig. 14, and serve to point out the smoothing effect of the auxiliary winding. The full-line curve in Fig. 14 (*a*) represents the voltage across the primary phases with the auxiliary delta opened, whilst the dotted curve shows the phase voltage with the auxiliary delta closed. The suppression of the harmonics is quite evident. The corresponding magnetizing currents are shown in Fig. 14 (*b*), the full-line curve again referring to the case where the delta was on open-circuit, and the dotted curve to the case where the delta was closed. The improvement in the primary magnetizing-current wave-form is again evident. In the latter case the auxiliary winding provides a portion of the M.M.F., and a current of irregular shape circulates around the closed delta in order to account for the difference between the two magnetizing currents in Fig. 14 (*b*). The magnetizing current circulating around the closed delta is shown in Fig. 14 (*c*). The small fundamental present in the wave is accounted for by the lack of balance of the various individual single-phase transformers. The oscillating voltage between the generator and primary neutrals is shown in Fig. 14 (*d*). With open-circuited delta (full line) the R.M.S. value of this voltage was 50 per cent of the R.M.S. phase voltage. This dropped to a negligible amount when the auxiliary delta was closed (dotted line).

In order to imitate the effects of a loose coupling between primary and auxiliary delta, reactance was

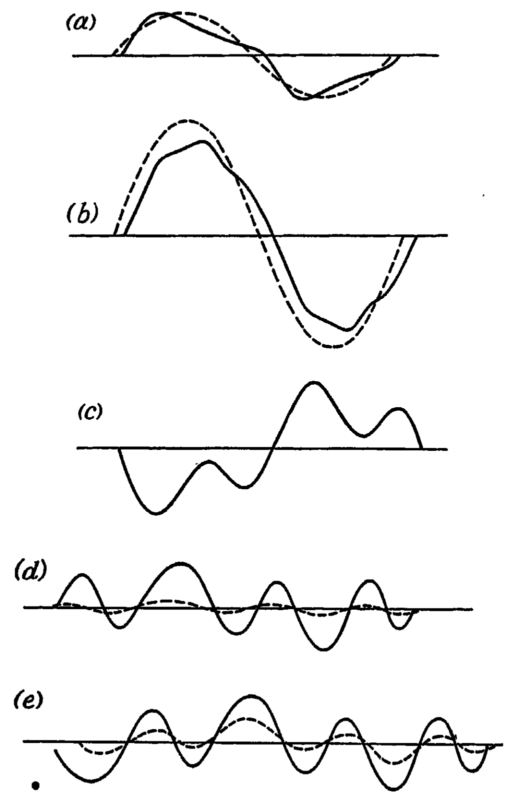


FIG. 14.—Oscillograms of tertiary delta. Primary neutral isolated.

(*a*) Wave-form of voltage across Primary (star) phases.
Full-line curve with delta open-circuited.
Dotted-line curve with delta on short-circuit.
(*b*) Wave-form of primary magnetizing current.
Full-line curve with delta open-circuited (R.M.S value 0·85 A).
Dotted line curve with delta on short-circuit (R.M.S. values :—Primary = 1·1 A; tertiary = 0·3 A).
(*c*) Wave-form of magnetizing current in delta (R.M.S. value = 0·3 A).
(*d*) Voltage waves between transformer primary and generator neutrals.
Full-line curve with delta open-circuited (R.M.S value = 50 V).
Dotted-line curve with delta on short-circuit. (R.M.S. voltage negligible.)
(*e*) Voltage waves between transformer primary and generator neutrals.
Full-line curve with delta open-circuited (R.M.S. value = 50 V).
Dotted-line curve with external reactance connected in circuit with delta (R.M.S. value = 20 V).

introduced into the latter. The oscillating voltage between generator and primary neutrals was considerably affected as shown in Fig. 14 (*e*), its R.M.S. value falling from 50 per cent to 20 per cent of that of the phase voltage. The loosely coupled tertiary delta is not so effective in damping out the voltage oscillation, but it is safer in the event of a fault.

Summary of star-star connections in order of preference.—(1) The best arrangement is with three-phase core-type transformers, the third-harmonic voltage being

reduced to a negligible value. The neutral may be either earthed or isolated. (2) With three-phase shell-type or three single-phase core- or shell-type transformers, the third-harmonic voltage being reduced to a negligible value, provided the transformer primary and generator neutrals are connected and they are fairly close together. This connection is quite satisfactory. (3) With three-phase shell-type transformers with tertiary delta the operating characteristics are superior to (1) and (2) if the tertiary delta has a low reactance, since the transformer operates as a star-delta transformer as regards magnetizing current. The cost of the tertiary winding solely for this purpose is, however, generally prohibitive. (4) With isolated neutrals, three-phase shell-type or three single-phase transformers of the core or shell type may give rise to harmonic voltages of as much as 50–60 per cent of the fundamental voltage. If they are provided with sufficient insulation to withstand the extra stresses set up there is no great objection, since the third-harmonic voltage does not appear between the lines. (5) With earthed neutrals the third-harmonic voltage may cause resonance with the line capacity and thus set up dangerous conditions. It is therefore not recommended.

Case 3: Star Interconnected-Star Connection.

(*a*) *Both neutrals isolated.*—There being no primary path for the third-harmonic magnetizing currents, this component is absent and the flux wave is correspondingly flat-topped. The primary phase voltage is peaked and the primary neutral is subjected to an oscillating potential. The six secondary windings also have third-harmonic voltages induced in them, but these cancel out in the two halves of each phase winding. Neglecting the other harmonics, therefore, the secondary phase voltage between line and neutral is sinusoidal. As there is no magnetization of the core from the secondary, there is no neutralizing of the flat-topped effect in the flux wave, such as occurs when the secondaries are connected in delta.

Whilst the trouble and possible danger of an oscillating neutral on the secondary side is removed, however, the effect appears again at the junctions of the two halves of each phase winding, for the potentials of these points oscillate about a mean value at third-harmonic frequency. This is not so troublesome as an oscillating neutral, and can be guarded against by the provision of adequate insulation. Moreover, the magnitude of the effect is only half as great as in the case of the plain star connections, for the two sections of the winding combining to bring about this result contain only half as many turns.

(*b*) *Generator and primary neutrals connected.*—This connection is similar to the one discussed in Case 1 (*c*), a greater or lesser amount of third-harmonic magnetizing current flowing in the primary circuit using the fourth conductor as a drain. The lower the resistance of the fourth wire or earth connections, the more closely will the flux wave approximate to the desired sine shape. There is no oscillation in the secondary neutral potential either with or without the fourth conductor, but the oscillation in the potentials of the mid-points of the secondary phases is very materially reduced by the additional connection, made either directly or by earthing. For the reasons already mentioned, however, this is not recommended.

(*c*) *Four-wire secondary.*—The provision of a fourth conductor on the secondary side does not affect the distribution of magnetizing current as it did with a plain star-connected four-wire secondary, as there is no resultant third-harmonic voltage set up in the secondary phase windings. The conditions are therefore the same as those in Case 3 (*a*).

Case 4: Interconnected Star-Star.

(*a*) *Both neutrals isolated.*—No third-harmonic magnetizing currents can flow in either primary or secondary, so that the flux wave is flat-topped. Third-harmonic E.M.F.'s will be induced in the secondary phases, giving rise to oscillation of the secondary neutral. Third-harmonic E.M.F.'s will also be induced in each half-phase of the primary, but these will cancel out between primary line and neutral, thus imparting to the latter a stable fixed potential. The potentials of the mid-points of the primary phases will oscillate as indicated in Case 3 (*a*). This oscillation, together with that of the secondary neutral, could be practically eliminated

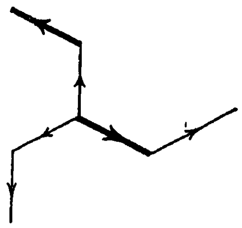


Fig. 15.—Showing impossibility of third-harmonic currents in interconnected primary.

by the introduction of a tertiary delta, but if this were done there would be no reason for interconnecting the primary windings.

(*b*) *Generator and primary neutrals connected.*—Assuming the generator supply pressure to be sinusoidal, no third-harmonic magnetizing current will flow, and the third-harmonic voltages in the two halves of each phase winding will balance each other. That no third-harmonic magnetizing current can flow can be seen by considering what would happen if it did. When the third-harmonic current is flowing through one half of the winding on any particular core, it is flowing in the *reverse* direction in the other half which is connected to the next phase (see Fig. 15), and as these currents are in phase with one another, but flowing through the winding in opposite directions at any given instant, they would produce no resultant M.M.F. on the core. As they cannot be set up directly by the impressed E.M.F., and as there is no cause for their self-inducement, they do not exist. Also, since there is no potential difference between the neutral points of the generator and the transformer primary, there is no third-harmonic magnetizing current flowing into the neutral point of the transformer primary, and hence through the windings.

The primary neutral potential is therefore stable and there is no need for the primary fourth conductor. The secondary neutral potential will oscillate as before.

Should the generator phase winding possess a third harmonic, however, quite a different set of conditions occurs. A third-harmonic current will now be forced round the three circuits consisting of generator phase winding, line, transformer primary phase windings and neutral return. The corresponding ampere-turns of each half of the transformer phase winding will now be neutralized by the ampere-turns of the next phase wound on the same limb, so that to all intents and purposes the transformer primary becomes non-inductive to the third-harmonic currents. The generator third-harmonic voltage is thus virtually on short-circuit, the current being limited only by its own impedance and the resistance of the external circuit. The current may therefore rise to a dangerous value, so that this connection should not be employed. Single earthing at either generator or transformer neutral is not, however, condemned.

(c) *Four-wire secondary.*—With this connection third-harmonic currents can circulate in the secondary circuit, thus making good the deficiency in the primary magnetizing current. The deformation of the flux wave will be reduced, although it cannot be eliminated, and the secondary neutral potential will be largely stabilized. The extent to which the latter is effected is dependent upon the magnitude of the secondary load, as this determines to a large extent the impedance offered to the flow of the third-harmonic currents. It will also be noticed that the distortion of the flux wave will decrease as the (lagging) power factor of the load is improved, since the presence of inductance in the load circuits tends to damp out the harmonics in the current wave.

The primary neutral potential is stable as before.

Comparison of the interconnected star and the tertiary delta.—It would appear from the foregoing that the interconnected star is unlikely to find an extensive field for the suppression of harmonic troubles. Due to the 30° phase displacement between the phase and line voltages, 15½ per cent more copper becomes necessary as compared with the straight star, in order that both transformers may be placed on the same basis as regards kVA rating. In addition to this disadvantage, the interconnection should be confined to the lower-voltage side, owing to the difficulties experienced in the interconnection of high-voltage windings. The cost per kVA of the interconnected transformer is increased, due to both reasons, whilst the insulation difficulties will possibly increase the liability to breakdown. Moreover, these disadvantages do not appear to be counterbalanced adequately by the advantages. Whilst the harmonics in the voltage waves are cancelled out in the two halves of the windings, the junctions of the windings oscillate, and the method of obtaining a sine wave of voltage seems to be inherently unsound.

On the other hand, the tertiary winding suppresses the third-harmonic voltages in the phases by providing for the sinusoidal magnetization of the core, i.e. by removing the cause of the third-harmonic troubles. Although the phase-voltage wave will always have a third-harmonic component, as previously explained, this will be very small since its only function is to circulate the harmonic magnetizing current in the tertiary delta. As in the case of the interconnected star, additional copper is required, but it is probable that in the case of the tertiary delta the extra cost represents a much sounder investment. The factor of safety is probably higher than in the case of the interconnected star, but the tertiary winding will have to be insulated for high potentials. The cost of the independent tertiary is, however, prohibitive, unless it is designed to supply a load also, and in this latter respect the claims of the interconnected tertiary cannot be ignored in those cases where the connection can be adopted. In this case the cost neither of insulation nor of copper is appreciably increased, for the whole of the tertiary winding normally operates at low potentials to earth. This connection, so far as the authors are aware, does not appear to have been made use of for the suppression of third-harmonic troubles, in spite of the fact that it seems to be particularly suited to certain cases, such as the provision of an alternative to the straight star-star connection for transforming up the generating pressure for transmission purposes. In this case the provision of the interconnected tertiary winding allows the good inherent characteristics of the star-star windings to be retained, and at the same time the dangerous conditions already referred to, consequent upon the presence of third-harmonic voltages acting in the transformer phases, appear to be averted.

From the point of view of stabilization of the neutral, the interconnected star winding is superior to the tertiary delta, since complete stabilization is afforded. Even in this case, however, the interconnected tertiary can become a powerful rival as, due to the close coupling, practically complete stabilization can be claimed, whilst the latter does not suffer from the disadvantage of mid-point oscillations. Where the secondary neutral is required for four-wire service or for earthing, there would appear to be no serious objection to placing the tertiary delta on the primary side. Expressions of opinion from designers concerning the utility of this connection would be very valuable.

Case 5: Star-Delta Connection.

(a) *Primary neutral isolated.*—As before, the primary magnetizing current drawn from the line cannot contain harmonics which are multiples of three, and in consequence the flux wave will have a tendency towards being flat-topped. The reactive E.M.F. in the primary phases and the induced secondary E.M.F.'s will as a result be peaked to a certain extent. The sine fundamental components of the secondary phase voltages add up to zero, when taken round the delta, but the third-harmonic components, being in phase with one another, are free to produce a magnetizing current circulating round the secondary delta. This current, neglecting losses, lags 90° behind the third-harmonic voltage, providing the ampere-turns for the production of a flux which will very nearly suppress the third-harmonic flux set up by the primary magnetizing current. These two opposing third-harmonic fluxes really only exist, of course, in their resultant. Another way of viewing the question is to regard the fundamental waves as operating on open-circuit or on normal load, whilst the third-harmonic

waves are operating on short-circuit and are thus very effectively damped down.

It is therefore seen that the generator will provide the fundamental, the transformer primaries the fifth, seventh, eleventh, etc., harmonics, whilst the secondary delta will provide the third, ninth, etc., harmonics of the currents necessary for the normal magnetization of the cores.

The mechanism of the operation is illustrated in Fig. 16, in which all the harmonics with the exception of the third have been neglected. In the left-hand group of curves, I_m represents the sinusoidal magnetizing current, split up into two components, I_f and I_h. The major component, I_f, consisting of fundamental and third harmonic is the magnetizing current necessary to produce the main sinusoidal primary flux represented by Φ_f in the right-hand group of curves. The harmonic component, I_h, gives rise to the hypothetical third harmonic flux represented by Φ_h. (It would also give rise to further harmonics, but these are neglected.) The main flux, Φ_f, induces the fundamental secondary E.M.F., E_f, and the harmonic flux, Φ_h, induces the harmonic E.M.F., E_h. The latter, being short-circuited, does not appear as a P.D. at the terminals and is absorbed in the windings. It does, however, give rise

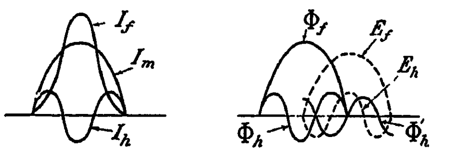


FIG. 16.—Magnetization from secondary delta.

to ampere-turns, which set up the hypothetical harmonic flux represented by Φ_h'. This is in direct phase opposition to the other hypothetical harmonic flux, Φ_h, the resultant of the two being almost nil. If all losses and magnetic leakages were neglected, the two would exactly counterbalance each other, the flux wave would be sinusoidal, and the secondary induced E.M.F. would contain no harmonics. Actually there is a minor flattening of the flux wave.

(*b*) *Generator and primary neutrals connected.*—In this case a closed path is provided for the third-harmonic components of the magnetizing currents, and these, in consequence, may be drawn from the line. The path provided consists of the generator phase winding, line conductors, transformer primary winding and neutral conductor, the last-named carrying a harmonic current equal to the sum of the third-harmonic components in the line conductors. It will be seen, therefore, that the third-harmonic current necessary for the normal magnetization of the core can flow in both the primary and secondary windings. In regard to the primary, however, since this current must circulate through the impedances of the conductors and the generator phase winding, it follows that its magnitude may be insufficient to produce, together with the fundamental current, a true sine wave of flux. The latter will therefore contain a third-harmonic component producing a certain amount of flattening of the wave. Due to this the primary reactive E.M.F. and the secondary induced E.M.F. will be peaked to a corresponding degree, and the third-harmonic components of the secondary voltage, operating under practically short-circuit conditions, will circulate a triple-frequency magnetizing current around the closed delta. As the impedance of the secondary delta path will be much lower than that of the corresponding primary path, it follows that the greater part of the third-harmonic magnetizing current will circulate around the secondary delta, and practically normal magnetization of the core will be effected. The flux and voltage waves will therefore be approximately sinusoidal.

(*c*) *Generator and primary neutrals earthed.*—This case is similar to the previous one, but the impedance of the paths of the third-harmonic magnetizing currents circulating in the primaries will be increased, since the resistance of the earth return will be greater than that of the fourth conductor. As a result, the secondary delta will carry a still greater proportion of the third-harmonic magnetizing current. If the generator neutral point be earthed through a resistance or reactance, the effect is still further to increase the triple-frequency current in the secondary, at the same time reducing the corresponding primary current. The limiting case is reached when the generator neutral is isolated, the whole of the third-harmonic magnetizing current now circulating around the secondary delta.

CASE 6: DELTA-STAR CONNECTION.

(*a*) *Secondary neutral isolated.*—Called into being by the peculiar shape of the *BH* curve, the third-harmonic magnetizing currents cannot flow back along the primary lines, but they can and do circulate around the primary delta, which provides a closed path for them. The complete magnetization of the core can thus be effected from the primary side, with the result that a sine wave of flux is set up. The induced E.M.F.'s are, therefore, also sinusoidal and the secondary neutral potential is stable. Even here a portion of the fifth, seventh, etc., harmonic components of the magnetizing current may flow in the secondary, if the relative impedance of the two sides is favourable to this.

(*b*) *Four-wire secondary.*—With this connection there is a closed path in both primary and secondary circuits for the third-harmonic magnetizing currents, and these flow in both sets of windings. The complete magnetizing current necessary for the establishment of a sine wave of flux does not come solely from the primary, and therefore there must be a certain amount of flattening of the flux wave, brought about by the introduction of a small third-harmonic component. This gives rise to small third-harmonic E.M.F.'s which make their appearance in the secondary phases. These in their turn set up third-harmonic currents which flow through the secondary phase windings of the transformer, the secondary line, and the load circuits, their arithmetical sum returning by way of the fourth wire. The impedances of these paths being relatively high compared with the impedance of the corresponding paths in the primary circuit, consisting of the phase windings forming the closed delta, it follows that the third-harmonic magnetizing currents flowing in the secondary will be small compared with those flowing in the primary circuit. The ratio which these two bear to one another is also

dependent upon the value of the secondary load, on light loads the secondary third-harmonic magnetizing current being almost negligible. In any case the bulk of this triple-frequency current circulates in the primary delta, with the result that the flux wave is almost sinusoidal. Again, the shape of the flux wave depends upon the magnitude of the secondary load, the deformation becoming less with decrease in load. Small third-harmonic E.M.F.'s are induced in the secondary phases, giving rise to the secondary third-harmonic magnetizing currents, and causing a certain amount of oscillation in the potential of the secondary neutral point. This oscillation increases somewhat with increase of load.

(*c*) *Secondary neutral earthed.*—This connection is similar to the previous case, but if the insulation resistance of the load is high, the whole of the third-harmonic magnetizing current necessary for the normal magnetization of the core will circulate in the primary delta.

If, however, the load be star-connected and its neutral point earthed, the connection becomes a variant of the previous case. The third-harmonic magnetizing currents circulating through the secondary phases, lines, load and earth, will be negligibly small owing to the resistance occurring in and adjacent to the earth plates. This connection would appear to be suitable for stepping up the generating pressure to a higher pressure (33 000–66 000 volts) for the transmission of large amounts of power to a distant load centre. In this case, where very high voltages or large capacities, or both, are involved, it is interesting to consider the effect of harmonics should the insulation near the neutral point of the star-connected primary of the transformer at the receiving end fail. In the event of this transformer being equipped with Merz-Price circulating-current protective gear, at least 5 per cent of the phase windings near the star point will usually be unprotected. If the coil insulation fails within the 5 per cent boundary, the protective gear will not operate and in consequence a completely closed circuit exists for the third-harmonic magnetizing currents, and their sum will circulate between earthing connections. The flux wave will then become slightly flat-topped, thus giving rise to the necessary third-harmonic voltage across the secondary phases for this purpose. It should be noticed that the harmonic voltage is free to circulate a third-harmonic capacity current and this will be developed by the capacity reactance of the circuit. Since the effect of the third-harmonic magnetizing currents is to tend to convert the flat-topped flux wave into a sine wave, it follows that the effect of the third-harmonic capacity current is to do the reverse, by endeavouring to set up a third-harmonic flux wave in phase with the fundamental flux wave. In other words, it will tend to make the flux wave more flat-topped and the voltage waves more peaked, as shown in Fig. 17.

It should be appreciated that the "flat-topping" effect of the capacity currents is nine times as great per volt as the "peaking" effect of the magnetizing currents.

The vector diagram in Fig. 17 also serves to illustrate a rather curious condition which may arise. Suppose that the third harmonic of the capacity current drawn from the supply is equal in magnitude to the third-harmonic current required for the normal magnetization of a transformer connected at the receiving end of a line. It will be seen that, neglecting the higher harmonics, no third-harmonic currents will be drawn from the generator, and in consequence the current wave at the sending end of the line will be sinusoidal. The amplitude of the third harmonic of the capacity current will, however, decrease uniformly (approximately) as the distance from the generator increases, whilst that of the third-harmonic magnetizing current will be constant. The distortion of the current wave will clearly increase uniformly and become a maximum at the receiving end of the line. As no harmonic currents are drawn from the generator it would appear that the capacity of the line serves a useful function in supplying the harmonic magnetizing current required by the transformer core, or, in other words, the conditions at the generating end are such as to produce complete current resonance at third-harmonic frequency. In this case the effect of earthing a circuit at more than one point will be considered, as this has been suggested

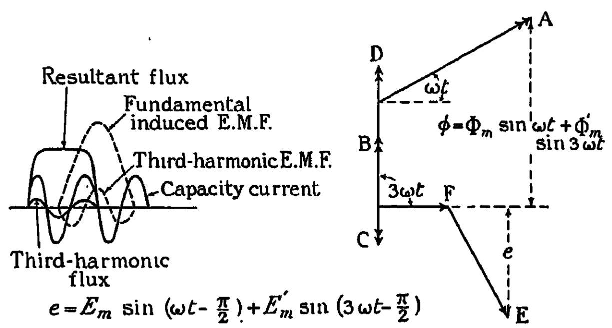


FIG. 17.—Effect of capacity currents.

A = Fundamental flux due to primary magnetizing current.
B = Third-harmonic flux due to primary magnetizing current.
C = Third-harmonic flux due to third-harmonic component of secondary E.M.F.
D = Third-harmonic flux due to secondary capacity currents.
E = Induced fundamental E.M.F.

in the case of two power houses tied together by means of an underground interconnector. If the pressure is stepped up at both ends and the high-voltage secondaries of both transformers are earthed, the third-harmonic components of the capacity currents will be relatively large, and a dangerous set of conditions may result due to the consequent large third-harmonic voltages across the transformer secondary phases.

It is pleasing to consider that in this instance the Postmaster-General's requirements in regard to earthing appear to be in line with the interests of power supply engineers.

CASE 7: DELTA-DELTA CONNECTION.

It is here possible for the third-harmonic magnetizing current to circulate freely in both closed deltas, so that as far as this component is concerned the core is magnetized from both primary and secondary. In order to induce the necessary secondary harmonic E.M.F. a certain flattening of the flux wave will be brought about, but this will be minimized by the secondary magnetizing effect, so that the resultant distortion is but small.

The third-harmonic magnetizing currents on the two sides will depend upon the relative impedances of the two deltas, being greater in the delta of the lower impedance. Assuming that these impedances are proportional to the square of the ratio of transformation, and taking into consideration the relative number of turns, it follows that the harmonic magnetizing ampere-turns will be equal on the two sides, neglecting losses and magnetic leakage.

CASE 8: TEE-TEE CONNECTION.

(a) *Both neutrals isolated.*—It will be assumed that the generator supplies a pure sine wave of E.M.F. to the primary of the transformer, and therefore it would appear that owing to a deficiency in the third-harmonic magnetizing current there will be a distortion of the flux waves in both of the magnetic cores. The fundamental primary currents flowing along *cd* and *bd* (see

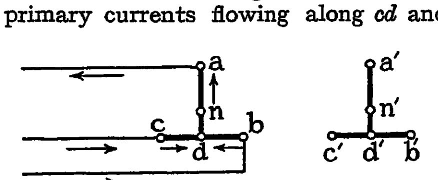


FIG. 18.—Tee-tee connection.

Fig. 18) are 120° out of phase with each other, or the fundamental primary currents flowing along *cd* and *db* are 60° out of phase with each other. Let each of these be imagined to produce its own sine wave of flux, together with its own flat-topped third-harmonic flux.

There are represented in Fig. 19, which also shows the two flat-topped fluxes, Φ_{cd} and Φ_{db}, due to the ampere-turns operating on *cd* and *db* respectively. The flux Φ_{cd} consists of a fundamental component, Φ_{cd1}, and a

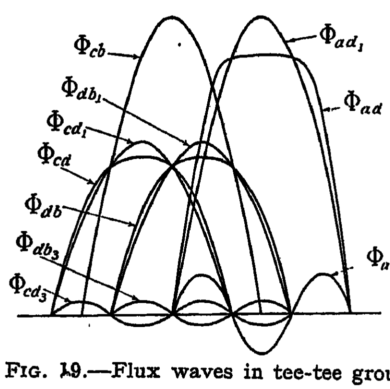


FIG. 19.—Flux waves in tee-tee group.

harmonic component, Φ_{cd3}. Similarly, Φ_{db} consists of the components Φ_{db1}, and Φ_{db3}. The final resultant of Φ_{cd} and Φ_{db} shows a sine wave of flux, Φ_{cb}, neglecting higher harmonics, this being 30° out of phase with each fundamental component, for the two harmonic fluxes neutralize each other. The latter, however, cause harmonic E.M.F.'s to be induced in the windings *cd* and *db*, and as the harmonic fluxes are equal and in exact phase opposition, so will be these harmonic E.M.F.'s. The point *d* will therefore oscillate at triple frequency. The fundamental voltages induced in *cd* and *bd* are 120° out of phase, but the third-harmonic voltages are in phase. As far as the latter are concerned the points *b* and *c* are equipotential.

Turning to the other winding, the primary fundamental current flowing along *ad* is 120° out of phase with that in *cd*. The flux due to *ad*, therefore, is 120° out of phase with the hypothetical flux due to *cd*, or 90° out of phase with the flux due to *cb*. This flux, Φ_{ad}, is assumed to be flat-topped to a certain extent, owing to a deficiency in harmonic magnetizing current. The third-harmonic flux, Φ_{ad3}, is in phase with the fundamental flux, Φ_{ad1}, due to ad_1, and therefore is in phase with the harmonic fluxes due to *cd* and *bd*. It thus appears that the harmonic E.M.F.'s induced in *cd*, *bd* and *ad* are all in phase with each other. The magnitudes of these harmonic E.M.F.'s are proportional to the products of flux and turns. In the case of *ad* both the turns and the flux are $\sqrt{3}$ times as great as in the case of *cd* and *bd*, and therefore the harmonic voltage induced in *ad* is three times the value of the corresponding voltage induced in *cd* or *bd*.

It is thus seen that whereas the "tee" system of connections is completely symmetrical as regards the fundamentals, it exhibits polarized symmetry only, when considered with reference to the third harmonics. From the latter point of view the points *c*, *b* and *n* are symmetrical and equipotential.

In the transformer secondaries, a third-harmonic voltage appears between lines *a′* and *b′*, none between *b′* and *c′*, and one equal and opposite to the first named between lines *c′* and *a′*. These unbalanced third-harmonic voltages produce unbalanced third-harmonic currents flowing round the secondary circuit.

Similar unbalanced reactive E.M.F.'s are set up in the primaries, causing a third-harmonic current to flow out by line *a*, this splitting up into two equal components at the neutral point of the generator and returning to the transformer by lines *c* and *b*. These currents, indicated by the arrows in Fig. 18, give rise to no resultant action on the winding *cb*, because their respective ampere-turns neutralize each other. The resultant sine wave of flux due to *cb* is therefore unaffected, but these currents will modify to a certain extent the magnitude of the potential oscillation of the point *d*. The third-harmonic current flowing in the winding *da* tends to eliminate the flat-topping harmonic in the flux wave by opposing Φ_{ad3}, but it cannot entirely neutralize it. The transformer does, however, attempt to supply its own magnetizing current, in view of the fact that the supply fails to do this completely.

The resultant fundamental ampere-turns acting on *cb* and on *ad* are exactly equal, for the fundamental currents are equal and the greater number of turns on *cb* is compensated for by the fact that the ampere-turns acting on *cd* and *db* are 60° out of phase with each other. It follows, therefore, that if the magnetic cores are the same and if *ad* is wound with 86·6 per cent of the turns of *cb*, the two fluxes are the same as far as the fundamental component is concerned. There is a slight difference due to the harmonic component of the flux.

In actual practice it is usual to make both windings alike, the additional 13·4 per cent of turns extending

beyond the point d. The far end of the winding is left open-circuited, and this point also is subjected to a certain oscillating potential.

The harmonics in the magnetizing currents and the potential oscillations set up are only of importance when a fair degree of saturation exists in the magnetic cores. If the transformers are worked on approximately the straight-line portion of the BH curve (say up to $B = 10\,000$ lines per cm^2), the effects will be inappreciable, but as the flux density is raised beyond this point they become more and more apparent.

The waves shown in Fig. 20 (*a*) and (*b*) illustrate these conditions. They refer to a small 6-kVA group normally operating on 100 volts, 50 cycles, with a maximum flux density of 10 000 lines per cm^2, but

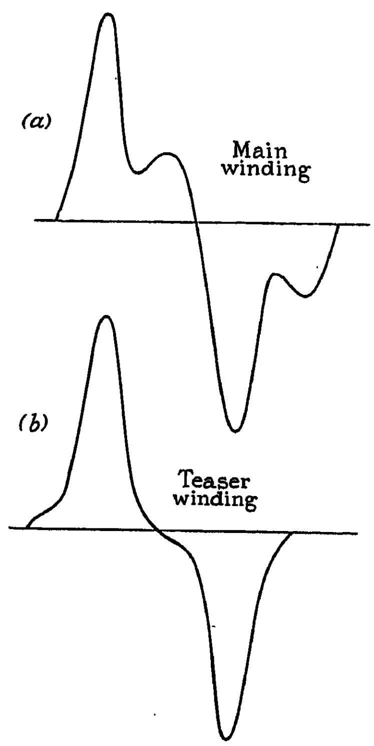


FIG. 20.—Magnetizing currents with tee-tee connections.

overrun so as to raise the maximum flux density to 14 000 lines per cm^2. With the primary system isolated from earth and the secondary on open circuit, Fig. 20 (*a*) represents the magnetizing current in the main winding and Fig. 20 (*b*) that in the teaser winding. When run on the normal voltage the waves exhibited similar characteristics but the harmonics were not so pronounced. The oscillations of the P.D. across various parts of the system also exhibited evidences of harmonics, but these were not of any practical importance. Considered as a whole, the harmonics are of much less importance than in the case of the star-star system of connections.

(*b*) *Both neutrals isolated. Secondary delivering four-wire supply.*—From what was said concerning the previous case, it will be seen that no harmonic currents will flow between the lines connected to the two ends of the 100 per cent winding and the neutral, for all three of these points are equipotential with reference to this harmonic. There is a third-harmonic difference of potential between the third line and the neutral point, however, and this will cause a third-harmonic current to circulate in this part of the secondary system, the currents in line wire and neutral being equal and opposite in phase. The value of this current will depend upon the magnitude and character of the load, in view of the fact that resistance, inductance and capacity affect the harmonic differently. This current will tend to neutralize the third-harmonic flux and will react in such a manner as to lessen the distortion of the resultant flux wave. This lessens the value of the induced third-harmonic E.M.F. and so the action tends towards a stable set of conditions. In the same way the unbalanced third-harmonic currents in the primary circuit are minimized. The system as a whole is still unbalanced, but to a lesser degree than in the former case.

(*c*) *Both neutrals isolated. Three-wire secondary line possessing appreciable capacity.*—It is interesting to consider the special case of a step-up transformer feeding a transmission system either underground or overhead in which capacity between cores and to earth, or alternatively between lines, is appreciable. There will be triple-frequency capacity currents flowing between lines a and b, and a and c, but none between lines b and c. The phase of these currents can be determined by reference to Fig. 19. The resultant third-harmonic E.M.F. acting between a and b (see Fig. 18) is the same as the third-harmonic E.M.F. between a and n, for there is no third-harmonic P.D. between n and b. This E.M.F. lags behind the flux Φ_{ad_3} by 90°, but as the resulting capacity current leads its E.M.F. by a corresponding angle, it follows that this current tends to set up a flux in phase with Φ_{ad_3}. In other words, it accentuates the magnetic distortion of the flux Φ_{ad}. The third-harmonic currents flowing out of lines b and c are equal in magnitude and phase, but exactly in phase opposition to the third-harmonic current flowing out of line a. Reference to Fig. 19 will show that these currents will tend to magnify the distortion in the flux, Φ_{db}, and to minimize it in the flux Φ_{cd}. The general effect is thus seen to unbalance still further the current and voltage relations in the whole system.

(*d*) *Generator and primary neutrals connected.*—The addition of a connection between the generator neutral and the transformer primary neutral will largely stabilize the potential of the latter point, and will cause a triple-frequency current to circulate between the line a and the neutral conductor. This will partially restore the distorted flux wave to its ideal sine shape, and will, to a corresponding extent, minimize the unbalanced third-harmonic voltages and currents in the secondary circuit.

If the neutrals are linked by means of earthing connections, either solidly or through resistances or reactances, then the stabilizing effects will not be so great, on account of the additional impedance offered to the third-harmonic currents.

CASE 9: SCOTT CONNECTION.

In the first place it will be assumed that the three-phase side is the primary, its neutral point n (see Fig. 21)

isolated, and that it is supplied from a generator giving a pure sine wave of E.M.F. The fundamental three-phase currents are balanced. As has already been shown, the flux wave due to the winding *ad* is distorted and exhibits the familiar flat-topped appearance, although not to any great extent. It follows, therefore, that while the induced E.M.F. in the secondary winding *c'b'* is approximately sinusoidal, that in the winding *a'd'* is peaked. The two secondary phases are not quite similar. When the group is placed on load a third-harmonic current will flow in the phase *a'd'* and this will tend to wipe out the third-harmonic flux in the core.

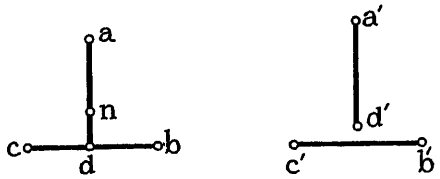


FIG. 21.—Scott connection.

The general tendency is to stabilize the primary potentials. A load of poor power factor is not so effective in this connection, as the presence of inductance in the secondary system tends to damp out the harmonic currents. Secondary inductance also alters the phase of the distorting flux harmonic.

When the three-phase primary operates with an earthed neutral, the generator neutral also being earthed, the case is similar to the plain tee-tee transformation already dealt with.

If the two-phase side is made the primary, the flux waves in both cores will be similar, and, since there is no inherent objection to the passage of third-harmonic currents, the flux waves will be sinusoidal. As a result no third-harmonic E.M.F.'s will be induced in the three-phase secondaries and, neglecting higher harmonics, the neutral potential will be stable. The question as to whether the phases are linked or independent on the two-phase side is immaterial.

CASE 10: VEE-VEE CONNECTION.

This system of connections is also unbalanced from the point of view of the third harmonic. If the primary

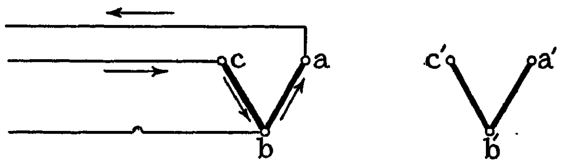


FIG. 22.—Vee-vee connection.

applied E.M.F. is sinusoidal in character, no third-harmonic magnetizing current will be supplied directly on account of this E.M.F., with the result that the two flux waves will be slightly flat-topped. The reactive E.M.F.'s in the windings *cb* and *ba* (see Fig. 22) will therefore contain third harmonic components tending to peak the respective waves. These harmonics will be equal in magnitude and will be exactly in phase, since the fundamentals are 120° out of phase. It follows, therefore, that there will be no resultant third-harmonic current flowing in the line *b*, but that a third-harmonic current will flow in each of the other two lines, these currents being equal and opposite.

Another way of looking at the problem is to consider the two lines connected to *c* and *a* respectively, together with the appropriate generator windings and the connecting lines, as forming the third circuit of a closed delta around which third-harmonic magnetizing currents can circulate. Owing to the fact that the impedance in the present case is greater than if a simple closed delta were employed, the third-harmonic magnetizing currents must fall short of the value requisite for pure sinusoidal magnetization. The flux waves cannot be entirely restored to their ideal shape, for in that event the third-harmonic magnetizing current would be reduced to zero. A reduction in the impedance of the circulating path would tend to increase the magnitude of the

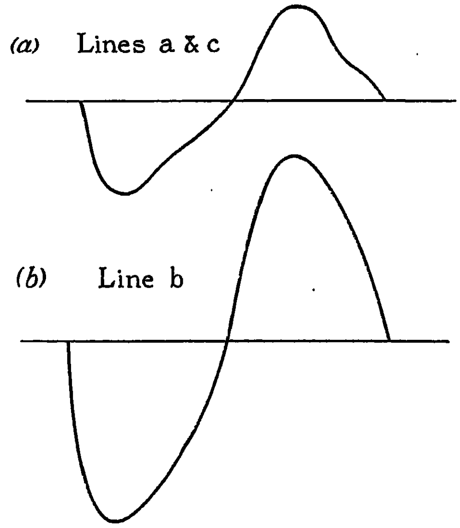


FIG. 23.—Magnetizing-current waves with vee-vee connections.

circulating harmonic current. This in its turn tends to reduce the flattening of the flux wave and so to reduce the magnitude of the third-harmonic E.M.F. The effect on the third-harmonic current, of reducing the impedance, is thus a differential one, but a low-impedance path does correspond to a closer approximation to sinusoidal conditions than a high one.

In the same way a circulating third-harmonic current will flow in the secondary system, in the lines connected to *c'* and *a'*. This current will also be determined to a great extent by the magnitude and power factor of the load, but again its tendency is to restore stable sinusoidal conditions.

With low or medium flux densities these effects are of small moment, but as one of the chief applications of this system of connections is for the starting apparatus used in conjunction with motors, first cost is an important consideration and higher flux densities are generally employed, particularly in view of the short-time rating usually adopted.

Oscillographic records (taken on two of the three

single-phase transformers used for the star-star tests) show that no appreciable distortion was introduced into the phase voltage, even when the group was worked at 40 per cent above normal pressure. The magnetizing currents naturally showed more distortion than when operated on normal voltage. Fig. 23 [(*a*) and (*b*)] shows examples of these magnetizing currents, Fig. 23 (*a*) representing the magnetizing current supplied to *a* (which was the same as that supplied to *c*) and Fig. 23 (*b*) that supplied to *b*. The latter wave shows a negligible amount of distortion, which was to be expected, whilst the former contains a considerable third harmonic.

Six-Phase Systems.

Case 11: Star Double-Star Connection.

There will be a certain amount of oscillation of the primary neutral potential, but it will be considerably less than in the case of the ordinary three-phase star-star transformation with both neutrals isolated, for closed paths for the third-harmonic magnetizing currents are found in the six-phase secondary.

Considering first the case where the primary neutral is isolated, the flux wave must exhibit a certain amount of flattening, on account of the usual absence of third-harmonic current in the primary, thus giving rise to the familiar peaked voltage wave in the secondary windings. Adjacent secondary phases being displaced by 60°, the third harmonics are all 180° out of phase with each other, or, in other words, are in exact phase opposition. Closed paths are therefore provided for the third-harmonic magnetizing currents to circulate in the secondary, phases 2, 4 and 6 forming the return paths for the currents in phases 1, 3 and 5. If the electrostatic capacities and insulation resistances between lines and to earth be uniform, the neutral point will take up a stable potential, but the line potentials will exhibit third-harmonic phenomena and will oscillate slightly due to the peaked phase voltages. The case is similar to the three-phase star-star transformation with four-wire secondary, except that three lines together with their respective phases act as the returns for the other three, instead of one conductor dealing with the summation of the three. If the electrostatic capacities and insulation resistances be unbalanced, the neutral will oscillate to a minor degree, but this will generally be unimportant. It is thus seen that the transformer cores can receive a certain amount of harmonic M.M.F. from the secondary system, making up to a large extent the deficiency in the primary currents. These "peaking" secondary ampere-turns tend to remove the flat tops of the flux waves, and reduce to a large extent the third-harmonic voltages in both primary and secondary. The effect is still further reduced in the case of a three-phase core-type transformer, on account of the interaction of the various magnetic fluxes. The flux waves, however, would only be restored to their ideal shape if the secondary system possessed zero impedance. In an actual case this is not quite achieved, but the resultant disturbance is small.

If the secondary neutral point is earthed, there will be no current in the additional circuit provided and, apart from electrostatic and electromagnetic balance, there is no change.

If the primary neutral point is earthed, capacity currents between primary lines and earth may, in part, provide the deficiency in the primary magnetizing current, as explained in Case 6 (*c*), thus helping to stabilize the neutral potential and to minimize the third harmonics in the secondary.

Case 12: Star-Diametric Connection.

If electrostatic and leakage balance is preserved, there is no difference between this and the previous case, for no current flowed into or out of the star point when it was earthed, and in the present instance the mid-point of each secondary takes up the same potential, with respect to both the fundamental and the third harmonic. It appears, therefore, as if the additional expense involved in bringing out the extra tappings is not justified, except for some special purpose such as for dealing with heavy out-of-balance currents in the case of a three-wire rotary converter. If these out-of-balance currents are not too large they can be balanced on one secondary winding alone.

Case 13: Star Double-Delta Connection.

This arrangement is practically the same as that discussed in Case 5, where a three-phase secondary was connected in delta. The third-harmonic magnetizing currents circulate round both secondary deltas, each of which provides half the third-harmonic M.M.F. for the magnetization of the transformer cores. The flux wave is almost restored to the sine shape, and the oscillation of the primary neutral potential is practically eliminated.

Case 14: Star-Double Interconnected Star Connection.

With this arrangement a considerable oscillation of the primary neutral potential would be met with, assuming it to be unconnected with the generator neutral. Due to the absence of primary third-harmonic currents, the flux wave would exhibit a certain amount of flattening and the phase voltage would be correspondingly peaked. With the interconnected-star arrangement there is no oscillation of the neutral potential, although the six mid-point tappings would oscillate. The adjacent phases are 180° out of phase with one another with respect to the third harmonic, but there is no third-harmonic circulating current since the resultant third-harmonic E.M.F. between line and neutral is zero in every case. There is therefore no damping of the primary neutral oscillation, as in the case of the plain double star. In spite of the added cost of bringing out the intermediate tappings, the interconnected double star is definitely inferior from the third-harmonic point of view.

Case 15: Star-Double Star-Tertiary Delta Connection.

There is no case for the introduction of a tertiary delta where six-phase secondaries are employed, for the third-harmonic currents can circulate in the secondaries,

thus damping down the osculation of the primary neutral.

Case 16: Interconnected Star Six-Phase Secondaries.

The advantage of an approximately stable neutral, one of the great points in favour of interconnected windings, is here obtained quite independently of the primary, as shown above, so that even when the primaries operate on a relatively low voltage there is no reason to adopt this costly arrangement.

Case 17: Delta-Double Star and Delta-Diametric Connections.

This arrangement is practically the same as Case 6. The flux wave is sinusoidal and there is no oscillation of the secondary neutral potential. Since closed third-harmonic paths exist in the secondary as well as in the primary, a portion of the third-harmonic M.M.F. will be supplied by each set of windings, but by far the greater proportion will be provided by the primary on account of the relative impedances in the two cases. The provision of an additional connection to the star point for d.c. three-wire balancing will also affect the result to a minor degree.

Case 18: Delta-Double Delta Connection.

The flux waves will be practically sinusoidal, but here again a portion of the third harmonic M.M.F. will be provided by each closed delta.

Case 19: Tee Double-Tee Connection.

The double-tee secondaries are balanced as regards fundamental voltages and currents, but are unbalanced from the point of view of the third harmonics. The three points b', c' and n' on one tee are equipotential (see Fig. 24), considering third-harmonic voltages, and

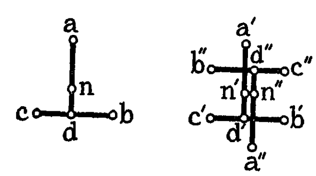


Fig. 24.—Tee double-tee connection.

similarly the three points b'', c'' and n'' on the other tee are equipotential. A third-harmonic voltage exists between a' and n', and an equal one between a'' and n''. Moreover, at the instant that a' is at its maximum positive potential with respect to n', at the same instant n'' is at its maximum positive potential with respect to a''. If the two neutral points n' and n'' are connected together there will be a third-harmonic voltage existing between a' and a'', equal to twice that between a' and n' or a'' and n''. The point a' will now have a harmonic difference of potential from all the other five phase terminals, and, since closed electrical paths exist in all cases, a series of third-harmonic currents are set up. The same state of affairs exists with respect to the point a''. No third-harmonic currents, however, circulate between points b', c', b'' and c''. In order to minimize these harmonic currents the two neutral points are not tied together solidly, but are connected through an inductance. This assists in limiting the unbalanced effects, but the two neutral points both oscillate about earth potential to a certain degree. The potential oscillations are not serious, but the harmonic currents set up may become troublesome on occasion. When the system is earthed this should be done at the middle point of this tie inductance. The flux wave in the transformer core corresponding to $b'c'$ and $b''c''$ will be approximately sinusoidal, but there will be a slight distortion of the flux wave in the other core.

When transforming from two to six phase by means of double Scott connections, the case is practically the same as for the ordinary Scott system described in Case 9.

Case 20: Vee Double-Vee Connection.

This case is practically the same as the plain three-phase vee-vee connection. Small third-harmonic E.M.F.'s are set up in all four secondary windings, and third-harmonic currents flow in the lines connected to a', c', d' and f' (see Fig. 25). The points b' and e' are

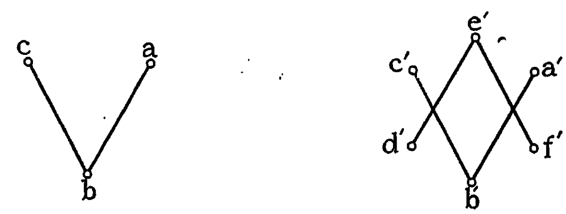


Fig. 25.—Vee double-vee connection.

stable from the third-harmonic point of view. These harmonic currents, together with the corresponding primary ones, tend towards the sinusoidal magnetization of the cores, and so their magnitudes are damped down by the very fact of their own existence.

The authors wish to express their thanks to the Governors of the Polytechnic and the Director of Education for facilities enabling the experimental work to be carried out.

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JUSTIFIABLE SMALL POWER PLANTS.

By A. B. MALLINSON, Member.

(*Paper received* 31*st October*, 1924; *read before the* NORTH-WESTERN CENTRE 3*rd February, and before the* SCOTTISH CENTRE 24*th April*, 1925.)

SUMMARY.

The paper generally has been written in the form of an introduction to justify small industrial power plants in areas where a supply is available, and to lead to a discussion on the subject.

Power plants, water, wind, by-product to process steam, from process refuse, household and town refuse, are all discussed, and finally a few comments are made on the small self-contained power plant relative to the super-power station and its network.

Examples are given of capital and operating costs of typical installations in various industries.

The vital importance of simplicity and minimum capital and operating costs to justify such plants is emphasized.

The slogans of "Conservation of our coal," "Super-power stations for cheap power," etc., have been so much in evidence recently, both in the lay Press and in political party speeches, that the general public doubtless feel that such statements are absolutely unanswerable. The object of this paper is to justify the use of the small power plant under suitable conditions.

What can be called a "justifiable small power plant"? The author suggests that a plant is justifiable when it can produce the required power—whether mechanically or electrically used—after allowing for all charges, both operating and capital, more cheaply than it can be purchased from the available outside supply.

Practicable sources of power supply are:—

(1) From water.
(2) From air.
(3) From heating and process steam, as a by-product.
(4) From a process refuse.
(5) From household and town refuse.
(6) From simple, self-contained stations.

(1) THE UTILIZATION OF OUR WATER POWER.

Whilst Great Britain can never, by reason of its geographical formation, produce much power from water, it is somewhat remarkable that in these days of dear coal and talk of the conservation of our coal reserves the water power used to-day, apart from three or four hydro-electric developments, is probably not one quarter of that used, say, 40 to 50 years ago in the days of cheap coal.

The reasons are mainly:—

(*a*) The tendency towards mechanical means, which has necessitated the water-wheel or turbine being augmented by steam power and has led, in many cases, when outside supply has become available, to electric power being installed, superseding both steam and water power.

(*b*) The gradual silting up of the rivers, causing loss of head, particularly in times of flood.

These small falls could be brought into use again if the work were done on the right lines. The author suggests that the layouts should be simple, with automatic or semi-automatic control. With the small powers to be dealt with, there is no margin for unnecessary elaboration in buildings, civil engineering, switchgear, stand-by plant or operation.

With a simple form of control it should be possible to utilize at frequent intervals the small falls along any river, and so avoid trouble with riparian rights, etc. In the United States this subject has recently been brought into prominence by a paper read by Mr. R. J. Wensley on "Present Practice in the Automatic Operation of Hydro-Electric Stations" at the Annual Convention of the American Institute of Electrical Engineers held at Chicago, 23rd–27th June, 1924. Mr. Wensley mentioned these systems as being regularly in use:—

(i) Control by water level, a float switch being employed to start up and stop at predetermined levels.

(ii) Control by system frequency, worked so that as the load comes on and the frequency drops, due to overloading of the running turbines, further turbines at other stations will start up. This is apt to be troublesome if several attempt to switch in at once, and is of no avail if any large station is in parallel on the network.

(iii) Remote control over a pilot wire. This is very effective when stations are not too far apart.

(iv) Supervision control over a telephone circuit. This system, which is now very largely used, enables the distant operator not only to start up, but also to get information in regard to head of water, gate opening, load in kilowatts, load on local feeders, etc.

(v) Control by manual operation of switch in station. This is effective when the size of plant merits a man being in attendance. The man is not expected to be constantly in the station, but to be available when called up by telephone.

(vi) Control by manipulation of the a.c. line. This is occasionally used, the plant in the remote station being started by closing the switch in the man-operated station, an a.c. relay then running the plant up.

(vii) Control by time switch. This can be used where the supply is to works, etc., where the maximum load is known in advance.

In this country the power obtained will generally be of the order of a few hundred down to 20–30 h.p.

There is obviously no possibility of putting such small plants in at a first cost per kilowatt comparable with that of a modern super-power layout, but, once equipped, the cost of operation on automatic or semi-automatic lines would be low.

(2) Power from the Wind.

During recent years several installations have been equipped for obtaining a certain amount of power from the wind. Such plants, provided that the battery is sufficiently large, and that there is, say, an oil-driven emergency set for use during calm periods, will, however, provide a means of obtaining a steady supply of power of only a few horse-power.

(3) Power as a By-product to Heating.

Where steam has to be raised for process or other work apart from power, there is the strongest possible case for the small power plant.

Such conditions occur in paper mills, bleach and dye works, chemical works, sugar and other refineries, public institutions, hotels, laundries, etc.

The cycles of heating and power must, of course, coincide fairly closely, but this will generally be found to be the case; the type of power unit, i.e. back pressure or pass-out, should be decided by a study of these cycles.

The pressures at which the steam is required for the heating process work are approximately:—

		lb./sq. in.
Paper mills	Machine driers	5–20
	Rag and esparto boilers	30–50
Bleach and dye works	Bleaching keirs	25–45
	Stenter heaters	15–40
	Drying cylinders	5–10
	Dye jigs	10–15
Chemical works (various uses)		10–60
Sugar refineries (evaporators, etc.)		10–60
Public institutions (calorifiers)		10–15
Hotels, etc. (kitchens)		5–10
Laundries		10–20

The difference in fuel consumption in raising this steam at, say, 160 or 180 lb./sq. in. in place of the used pressure is very small; for instance, the total heat in steam at 160 lb./sq. in. is only 3 per cent greater than at 20 lb./sq. in.

Actual tests on a large number of installations have shown that even with saturated steam used under favourable conditions the steam loss in passing through the power plant is only ·5–6 per cent. The figure of 10 per cent taken by the author in arriving at the cost per unit is therefore a very liberal one.

In most cases it will be found that the demand for heating steam is more than sufficient to supply all the power requirements of the factory. Under some conditions the margin is such that an appreciable outside supply could be given; a case in point is the sugar refinery at Glebe, recently put into operation with the Greenock Corporation supply.

Where the fluctuations of demand for heating steam are great, e.g. for grass and wood digesters in paper mills, and bleaching keirs and dye houses in finishing works, the introduction of a heat accumulator is desirable. The Ruth accumulator has, during the past few years, been largely adopted on the Continent for this purpose.

Where steam is required for direct heating, no oil must be used—a condition easily fulfilled by using either engines with no cylinder lubrication, or turbines. Superheated steam is generally avoided for heating, but for long pipe runs a little is advantageous to avoid undue pipe losses.

Paper Mills.

The author covered the subject fairly fully in his paper entitled "Electric Driving in the Paper Mill on Heat-Economy Lines." *

The typical case of a British esparto mill boiling 190–200 tons of grass per week may be quoted.

	lb. per hour
Steam for grass-boiling at 45 lb./sq. in.	2 000–10 000
Steam for paper-making at 15 lb./sq. in.	8 000–10 000
Steam for coating at 15 lb./sq. in.	5 000– 8 000
Steam for recovery, breakers, potchers, and general at 20 lb./sq. in.	5 000– 7 000
Total	20 000–35 000

The boiler pressure being 175 lb./sq. in., a pass-out power plant of 600–700 kW to supply the whole of the electric load in the mill is a sound proposition.

Capital cost.

	£
650-kW geared pass-out turbo-generator	7 500
Switchboard extension	250
Wiring	250
Pipework, valves and covering	2 000
Foundations, structural alterations, etc.	1 500
Labour and contingencies	1 000
Total outlay	£12 500

Operating conditions.—132-hour week; 50 weeks per year; 350 kW average load; 2 000 000 units per annum; power plant steam consumption, average extra over heating steam taken at 0·5 lb. per kWh.

Operating cost.

	£
560 tons of coal at 24s.	672
112 tons of ash handled at 3s.	17
Supervision of plant	50
Oil and stores	50
Repairs	100
Insurances	50
Net cost per annum	£939
Net cost per unit, 0·113d.	
Interest and depreciation, 10 per cent on £12 500	1 250
Gross cost per annum	£2 189
Gross cost per unit, 0·263d.	

* *Journal I.E.E.*, 1921, vol. 59, p. 538.

No engine attendants are allowed for, because the man looking after the main engine can supervise this power unit, provided it is put in the same room.

Bleach and Dye Works.

The conditions here are very similar to those obtaining in paper mills, except as regards running hours and load factor. The following data concern a typical works near Manchester.

Capital cost.

	£
Two 150-kW back-pressure sets	2 500
Switchboard (for power plant only)	200
Wiring	100
Pipework and valves and pipe covering ..	2 000
Foundations, structural alterations, crane, etc. ..	1 000
Contingencies	250
Total	£6 050

Operating conditions.—48-hour week, 50 weeks per year; 360 000 units per annum; 10 per cent of engine steam consumption, representing power production (8/1 evaporation) = 265 625 lb. coal (118·5 tons), say 120 tons.

Operating cost.

	£
120 tons of coal at 24s.	144
24 tons ash carted away	4
Stokers	nil
Engine tender	200
Supervision by engineer	50
Oil and stores	40
Repairs	50
Insurances	40
Net cost per annum	£528
Net cost per unit, 0·352d.	
Interest and depreciation, 10 per cent on £6 050	605
Gross cost per annum	£1 133
Gross cost per unit, 0·756d.*	

Mental Institution.

(Rated capacity 1 300 beds.)

Capital cost.

	£
Three 75-kW sets (back-pressure)	2 850
Switchboard	300
Storage battery and booster	1 650
Wiring	150
Pipework, etc.	600
Foundations, structural alterations, crane, etc. ..	1 500
Contingencies	55
Total	£7 700

Operating conditions.—108-hour week, 52 weeks per year; 224 000 units per annum; engine steam, ½ lb. coal per unit, all exhaust being used for heating = 50 tons of coal.

* Public supply:—1·5d. to 0·875d. (various examples).

Operating cost.

	£
50 tons of coal at 24s.	60
10 tons ash handled at 3s.	1·5
Oil and stores	40
Repairs	34
Battery maintenance	260
Insurances	25·5
Extra staff, £3 per week	156
Net cost per annum	£577
Net cost per unit, 0·618d.	
Interest and depreciation, 10 per cent on £7 700	770
Gross cost per annum	£1 347
Gross cost per unit, 1·45d.*	

These three typical cases suffice to show the possibilities of such power plants to generate at an appreciably lower rate than that at which an outside supply can be obtained. They also show the limitations of such plants as regards capital expenditure. The paper mill with its 132-hour week obviously provides the best figure of gross cost per unit; with those plants operating one or two shifts per day, the interest and depreciation item amounts to nearly double the generating cost. It is therefore of vital importance in installing such plants to employ the simplest layouts and concentrate the capital cost as far as possible in the producing equipment; to make a central station in miniature simply means saddling the operating cost with an overwhelming charge.

These figures are fairly self-explanatory, the items requiring explanation being probably the following:—

(*a*) That no capital or operating cost is given for steam-raising plant. The boilers are required for the production of steam for heating, whether the power plant is installed or not, and the stokers have to be there to fire the boilers to raise the steam for heating. The extra 10 per cent of fuel consumed will entail no extra labour, except under exceptional conditions with the steam plant already working up to its limit.

The author's experience is that these steam-raising plants are almost invariably larger than actually required, in order to provide for possible peaks, and are consequently lightly rated.

(*b*) The high cost of pipework. The distribution of low-pressure steam requires a new pipe layout, all pipes being increased to pass the required volume at the lower pressure. In addition, these pipes, in order to secure efficiency, cannot be too well covered.

As power plants on these lines show such low operating costs, why is it that so many works where these conditions exist have taken a public supply? Two typical cases, both with 10-year agreements, for instance are:—

A bleach and dye works with five Lancashire boilers under steam at 120 lb./sq. in. reduced to 15–20 lb./sq. in. for process work, and 100 000 units per month purchased from the supply.

An esparto paper mill using 10 000–12 000 lb. of steam per hour at 180 lb./sq. in., reduced to 50 lb./sq. in.

* In this case an offer for a supply was 3½d. per unit.

for process work, whilst a steady 250 kW is taken from the public supply mains.

The author suggests that the main reasons are :—

(*a*) The possibility that in some cases the boilers were getting old and new boilers would have been required.

(*b*) The capital outlay that would be incurred in installing the plant.

(*c*) The greater reliability of the public supply.

(*d*) The manner in which the case has been put forward by the supply undertaking.

(4) Power from Process Refuse.

The principal sources of process refuse in this country are wood-working establishments of all kinds, tanneries, and blast furnaces, coke ovens, steelworks, etc.

Whilst in the wood-working trades, refuse is utilized for power purposes to a considerable extent, either to raise steam in a more or less efficient manner or in gas-producers, there is a large quantity not effectively dealt with. In a city like Manchester, for example, there are about 100 wood-working establishments—sawmills, builders, joiners, furniture makers, wood box and case makers, etc., producing probably 750–1 000 tons of refuse per week, whilst throughout the country it probably amounts to 100 000 tons or more.

The present outlets for this refuse are :—

(A) As firewood (often a perquisite to the carters).

(B) Sawdust for bedding horses, afterwards being used as manure. Before the European war the bulk of the sawdust produced was disposed of in this manner, but mechanical transport has greatly reduced the quantity. The present price obtained is about 16s. per ton, the purchaser having to provide bags and do the necessary carting.

(C) For kippering at the fishing ports.

(D) Shavings for gas filters and packing; there is a comparatively small demand for this purpose.

(E) For use in firelighters; for this also there is a relatively small demand.

In a typical saw-mill, case and box works cutting up about 55 standards (137·5 tons) per week, the refuse produced during a week averaged per hour :—

	lb.
Cross-cut ends of deals	83
Black board sides	174
Long shooter shavings	11
4-cutter dubbings	90
Sawdust	769
	1 127

This is equivalent to 60 855 lb. per week (say 27 tons or 19·6 per cent of the total). At this works the power required is 100–120 kW.

In existing wood-working shops the layout is in general compactly grouped round the boiler and engine; to introduce a new power plant entails either putting it in a vacant space away from where the refuse is produced —entailing a material increase in the cost of handling the refuse—or shutting down the plant for a month or two while the old plant can be dismantled, structural alterations affected, foundations put in and new plant erected. In consequence the owners usually take a public supply and scrap their engine, and are still faced with the problem of the disposal of the refuse.

In this respect much can be done by the adoption of a more broadminded attitude by the supply undertaking. The author suggests that the ideal method is for works to adopt the electric drive, taking the public supply, and then to scrap the old power plant and install an up-to-date wood-refuse power plant in the central position. Then, when in operation, the public supply could be retained as a stand-by to whatever extent may be agreed upon, the consumer guaranteeing a certain minimum cost per annum.

If, as will often be found to be the case, the power required exceeds that which the refuse can generate, a section of the works could be permanently connected to the outside supply.

On such lines any factory, no matter how cramped its layout, can be modernized and will operate in the most economical manner—economical not only from the user's point of view but also from that of the national interests.

Such power plants can be either (1) steam with suitable combustion chambers, or (2) gas with suction producers, the former requiring from 4 to $4\frac{1}{2}$ lb. of refuse per b.h.p.-hour, and the latter from $2\frac{1}{2}$ to $3\frac{1}{2}$ lb.

Typical City Saw-mill Installation.

(Steam plant fired with refuse in an underground step grate, locomotive-type tubular boiler.)

Capital cost.

	£
130–150 h.p. locomobile steam plant	1 800
Dynamo belt drive	400
Foundations	350
Switchboard	200
Wiring	100
Pipework and sundries	200
Structural alterations	300
Contingencies	250
Total	£3 600

Whilst gas is the more economical on paper, there are other factors, such as the provision of steam for seasoning, heating, etc., and the class of refuse produced, which must be taken into consideration.

Operating conditions.—48-hour week, 50 weeks per year; town's water to boiler; 168 000 units generated per annum.

Operating cost.

	£
Labour: Fireman	175
Labour: Engine tender	195
Water	15
Oil and Stores	35
Insurance	15
Maintenance	50
Net cost per annum	£485
Net cost per unit, 0·692d.	
Interest and depreciation, 10 per cent on £3 600	360
Gross cost per annum	£845
Gross cost per unit, 1·21d.	

A public supply is available at 1·25d. per unit. If used, however, material charges for handling and disposal of the refuse must be added. In addition, the steam provided for canteen cooking, office and shop heating is not taken into account.

Bobbin Works.

(Steam plant fired with wood refuse, underground step grate and locomotive-type tubular boiler.)

Capital cost.

	£
420–515 h.p. locomobile	4 500
Direct-coupled alternator	2 500
Switchboard	400
Wiring	200
Pipework, etc.	150
Foundations	500
Structural alterations in old engine house	1 000
Contingencies	550
Total	£9 800

Operating conditions.—275 kW steady average load, 660 000 units per annum.

Operating cost.

	£
Engine tender	200
Fireman	175
Town's water	35
Oil and stores	75
Insurances	30
Maintenance, furnace and plant	150
Net cost per annum	£665
Net cost per unit, 0·242d.	
Interest and depreciation, 10 per cent on £9 800	980
Gross cost per annum	£1 645
Gross cost per unit, 0·6d.	

Steam is also used for drying stoves.

Builder's Saw-mill and Joinery Works.

(Driven by wood-refuse gas plant.)

Capital cost.

180-h.p. wood-refuse gas plant and engine and generator, delivered and fixed	2 500
Switchboard	200
Wiring	100
Pipework	250
Foundations	200
Structural alterations	300
Contingencies	250
Total	£3 800

Operating conditions.—48-hour week, 50 weeks per year; 168 000 units generated per annum.

Operating cost.

	£
Labour: engine tender and plant attendant	200
Boy assistant	100
Supervision from engineer	50
Oil and stores	35
Insurances	15
Maintenance	50
Net cost per annum	£450
Net cost per unit, 0·643d.	
Interest and depreciation, 10 per cent on £3 800	380
Gross cost per annum	£830
Gross cost per unit, 1·19d.	

Plants of this character can very often be installed as a direct drive. This would reduce the capital cost by, say, £500.

Refuse-gas plants are now well past the experimental stage. They are adaptable to a wide range of waste products available in this country, from wood refuse of all kinds to tannery refuse, barks, etc., and even stable manure.

Surplus Gas: Blast-furnaces, Coke Ovens, Etc.

The utilization of surplus gas for power purposes is now practically universal. Such plants have been highly developed and in some areas, such as the North-East Coast, the power plants so operated feed into the public supply networks. Until a few years ago, plants were generally gas-engine driven, but the later developments have in the main been by steam turbines from gas-fired boilers.

(5) Household and Town Refuse.

The refuse destructor has long ago proved the practicability of power generation from town refuse. Such plants may be small, but all tend to the common end, i.e. national economy, and as such should receive every encouragement. There are undoubted difficulties in their extended adoption, such as small capacity, cost of staff, dusty surroundings, etc. The author suggests that the financial results obtained with this type of plant could often be improved if steam were sold for heating in addition to the production of power. The difficulties caused by a fluctuation of the calorific value of refuse, etc., would be overcome by the installation of stand-by or emergency oil engines.

(6) Simple, Self-contained Power Stations.

Whilst primarily this paper has been written to deal with the small power station fed with refuse, or steam as a by-product, there is, in the author's opinion, in many places at least a strongly debatable case to be made out for the self-contained small station. The capital outlay for super-power stations, long transmission lines, substations and the like, is very large, and this must introduce a heavy charge on the cost per unit in scattered areas with a low load factor.

In a typical example with a steam-driven station of 2 500 h.p. capacity, the total generating cost, including

rates and taxes, is 1·0d. per unit, part of the plant being over 20 years old.

With the highly efficient steam or oil prime movers available to-day, these small stations show very favourable results. The tables of electric supply undertakings published with the *Electrical Times* show many small stations with total works costs of 2d. and over per unit, but the author suggests that it is not fair to compare the modern super-power station operating costs with these, which are generally for more or less old and inefficient plants. If a new super-power station and its network were to be compared with new, small power plants of the most efficient type, there would at least be a case for argument. The author hopes that this most debatable part of the subject of power generation and distribution will be dealt with in the discussion.

Conclusions.

The predominant factor in all considerations of small power plants is capital cost. The figures quoted of different installations which have been quoted emphasize this clearly. There is no room for "frills"—miniature central stations and the like—and nothing but bare necessities should be installed. In the same way the operating costs must be kept down, especially on these small stations having low load factors.

Discussion before the North-Western Centre, at Manchester, 3 February, 1925.

Mr. S. J. Watson: With many of the author's statements I am in cordial agreement. There are undoubtedly many cases in this country where steam or burnable material is wasted which might otherwise be used with great advantage by the owners of the plant. I think that his remarks particularly apply to such industries as the paper-making and wood-working trades. In a number of instances wood-working machinery is entirely driven by gas produced from the waste wood which is torn off in trimming, etc. Under such conditions it is absolutely impossible for any supply undertaking to compete. It is utilizing, under extremely efficient conditions, what would otherwise be absolutely waste material. With many of the estimates put forward by the author I do not agree. In these estimates he shows the amount of power used, and the annual output obtained, but he does not attempt to charge anything at all for the capital expenditure on buildings or boilers, nor, in the majority of cases, for the wages of operators. I am aware that in the course of the paper he excuses himself by reason of the fact that much of the plant would be installed in any case, but it might equally be said that the plant was originally installed for power purposes and was subsequently used for heating purposes. I suggest quite seriously that if he is going to make such comparisons he ought at least to take into account a portion of the capital charges and working expenses which are justly attributed to the work done by the plant. If he does that, the final figures of cost per unit will be much altered. Another point to which I take exception is that the author charges a very small amount for repairs. It is quite true that he takes 10 per cent for interest and depreciation, but I find that in many cases he has included storage batteries, and many of us know to our cost what the maintenance of a storage battery entails. He has only included something less that 1 per cent, and I venture to suggest that he ought to make a very much larger allowance. One of the reasons why manufacturers prefer to take a supply from a public source is that the responsibility for generating their own supplies is a constant source of worry and trouble to them. Dealing with the subject from a rather broader aspect, supply undertakings are constantly experiencing the case of manufacturers who have put in their own plant and find it to their advantage later on to discard it and use the public supply. Such changes apply not only to what I may call "straight" power industrial undertakings but also to the particular types of industry which the author singles out to show that it is an advantage to generate their own power, such as dye works, for instance. Numbers of such works utilize the public supply. Many of them deliberately discard their own plant and the problematical savings which they may effect by its use and come upon the public supply mains, thus indicating clearly that they consider that there is an advantage in so doing. Apart from certain very special cases, the costs per unit given by the author are not as low as those of many power supply undertakings in the country for similar supplies. As an instance, two or three years ago I was interested in a very large paper mill which required some 200 or 300 additional horse-power, equal to a consumption of about 2 million units a year. I negotiated with the local supply undertaking, and the lowest price that they were prepared to quote for the supply was 1¼d. a unit. Such a price was, of course, quite unreasonable. At that time I was associated with an undertaking which was supplying energy at less than 0·50d. per unit. The reason why greater progress is not made is very often that the supply undertaking does not take the long view in regard to this matter. I think, however, that all over the South-East Lancashire district the prices at which power is supplied to-day do not vary very much from most of the figures given by the author. The author includes no item for local rates. No concern can spend £12 500 in increasing the value of their property without the knowledge (sooner or later) of the local assessors, and rates and taxes to-day represent no small proportion of the cost which the supply undertaking has to bear. One of the most important reasons why the combined use of steam for power and for process work does not make greater progress is that in many cases the time when the maximum amount of steam is required for process-work does not coincide with the time when the maximum amount of steam is required for power purposes. In such cases it is impossible to get the best results out of the combination. Another point is that most of the figures given in the paper are for single private plants, whereas in connection with supply undertakings considerable expense is incurred in providing spare plant so that an uninterrupted supply

can be maintained. The time lost to manufacturers through interruptions of the public supply is very much smaller than in cases where the plant is installed on the premises. There again by taking a public supply the manufacturer stands to gain. I entirely agree with the author that we in this country have not made as much use as we should have done of the large aggregate amount of small power available from our streams. In this district there are a number of cases where the river water, in passing over the weirs, is at a head of from 6 to 8 ft. My undertaking keeps records of the flow which comes through Salford and we know that it varies from about 2 million gallons up to 30 or 40 million gallons per hour. This represents a very considerable amount of power. I agree with the author that in the future it should be made compulsory to take advantage of such natural power supplies where they exist. I have been associated with refuse destructor plants on one or two occasions, and the most satisfactory one of which I heard was in a town in South Wales where the value of the ashes was high, inasmuch as free coal was supplied to the miners. This particular undertaking was burning the ashes in a destructor and obtaining sufficient steam to generate between 2 and 3 million units a year, which were sold to a power undertaking. Many others, owing to the nature of the refuse, were hardly producing sufficient steam to run their forced-draught fans, and in some cases they even had to supplement the refuse by means of coal in order to maintain the plant in operation.

Mr. J. Frith: I quite agree with the author that the supply undertaking should, and in most cases will, help a firm to install a power plant of its own. I have even known cases where the supply undertaking has not only provided a stand-by supply but has bought the surplus energy. I also agree that in many cases small self-contained generating plants can be put in and show a good financial comparison with purchased power. They can be of a type which requires very little attention, are cheap to maintain and have none of several very large items of expense which the supply undertaking has. It is certainly surprising, as the author says, that so little of the water power of English rivers is used. I have been connected with one or two water-power projects and I have been equally surprised to find the number of people who have water rights on our rivers. The vested interests are very difficult to override, but Parliament might possibly take steps to dispossess the owners. The author does not mention waste-heat plants; just lately I have been concerned with several boiler plants making large quantities of steam from otherwise absolutely waste heat.

Mr. A. E. Clarke: I think that we are rather apt to consider in these days of super-stations that a public supply is the cheapest and best source of power, whereas in certain circumstances this idea may prove fallacious. As the author suggests, there are undoubtedly many applications for which a strong case may be made out for private power plants. It is necessary to proceed most cautiously, however, because in some cases it is fairly easy to prove on paper that private supply would be the cheaper, whereas in practice the reverse is proved to be the case, and vice versa. In this neighbourhood there is a flour mill which was erected some time previous to 1914, a replica of a steam-driven mill the property of the same company. The directors decided to install electric drive and to purchase their supply from the local authority. At the time a comparison on paper of the costs of steam and electric driving showed a decided gain in favour of steam, but they believed that as the use of electricity extended, so costs would come down until no difference existed between the expenses of the two methods. At first the experiment proved costly, but since then for a variety of reasons the output of the mill has been nearly doubled, and the cost of power per sack of flour reduced until it is lower than that of similar mills running at present under steam drive. So satisfied are the directors with their experience that they have under consideration the complete change from steam to electric drive in other mills. They recently purchased a mill which up to the time it was bought was driven by gas-producer plant, and after a short experience of this method of drive they have scrapped the gas engines and producer and are taking a supply from the local supply undertaking. Here was a case in which it was demonstrable on paper that with a load factor of 65 per cent private supply would be the cheaper, whereas the opposite has been proved in practice. I shall now give an illustration to show the other side of the question. A small plant of 100 h.p. produced a certain article from wood balks in which the operating conditions were difficult on account of the heavy intermittent loads. The load factor was only 16 per cent, and the net rate per unit high. Here the power charges constituted a large proportion of the manufacturing costs, a proportion so high as to cut out all profit at the prices obtainable. The consumer was rapidly becoming insolvent and, after discussion with a well-known manufacturer of oil engines, decided, under very generous terms on the part of the engine makers, to install a semi-Diesel engine. This was done about 18 months ago, and the result is that the power costs are now roughly one-third of the supply undertaking's charge. Now mark the importance of power supply in its incidence on manufacturing costs. This consumer after the installation of the engine was, in virtue of his lower manufacturing costs, able to cut his prices and more business resulted until he was able to run his plant 100 hours per week. This of course resulted in a further reduction in his costs, by means of which he has been able to keep his plant in full operation, has paid for his engine and is now making quite handsome profits. I am thoroughly in agreement with the author's views as to supply in special cases and could quote several examples of saw-mills, wood-working shops and works using steam in the production of various manufactured articles, all obtaining their power as a by-product, in which the supply undertaking's price is cut by a large percentage. The true conception of the power problem appears to me to be that each case must be considered on its merits, and that only after meticulous investigation and with the greatest discretion must a decision be come to as to which method is the more advantageous.

Mr. G. F. Sills: It should be remembered that the author is making out a case for a few trades only, because in the ordinary factory working 8 hours a day, with little

or no low-pressure steam required for process work or heating, it is normally impossible to generate any more cheaply than to buy power from a moderately large supply undertaking. The author makes no allowance for management costs; these should be taken into account. The great advantage in buying power consists in the reserve plant available in public generating stations; it is very unusual for a private plant to have any stand-by. In the normal factory any small saving made in generating its own power would be cancelled if a stand-by were installed. Many factories would rather pay a little more for bought power to save the extra capital outlay in purchasing their own generating plant. A good arrangement where low-pressure process steam is required is to put in a steam set to use all the high-pressure steam for generating power, then to send the exhaust or pass-out steam to the process work, etc., electric power that cannot be supplied by this steam plant being purchased from an outside source. A case came to my notice only a few days ago, where a few thousand pounds of low-pressure steam were required for process work on a 24 hours' load. The factory manager proposed to install a 160-lb. boiler and a steam set to use all the high-pressure steam available, to use the low-pressure steam at 10–15 lb./sq. in., and to buy the remainder of the electric power required. It will be realized that the boiler had to be used in any case, and about half a million units could be generated a year for the capital cost of the steam set plus about 10 per cent on the cost of the fuel—representing the extra cost of first using the high-pressure steam in the manner indicated. The supply undertaking had sent in the printed agreement which stipulated that all electric power used should come from their mains. Surely it is in everyone's interest to obtain the maximum benefit from every pound of coal, and I would suggest that it is against the interests of any public supply undertaking to make such a suggestion in these circumstances. The supply undertaking actually argued that the buyer should not make use of his steam as explained above. When they were told that if they still insisted the factory would generate all its own power they gave way. The author gives some figures referring to costs of insurance. Is this why the repair charges in the tables appear to be on the low side? On a plant where process steam is required and a small generating set is used, it should be possible to have one man to look after the boiler and the set. I understand that in one case it was doubtful if the local unions would agree to one man doing this work, and it seems more than absurd if this is so, as it means an unnecessary addition of £4 per week per shift to the generating costs. Referring to the question of water supply, I believe that the Electricity Commissioners have power to adjudicate in these matters. In connection with power-supply charges, manufacturing firms get out a good many schemes for private generating plants for factories already buying power from a public source. It is probable that these schemes are often only a means of forcing the supply authority to reduce the cost of power. Referring to the author's remarks about blast furnaces, is it not a fact that most of the large steelworks in this country use the blast-furnace gases in gas-engine generating sets, and do not normally burn the gases under boilers?

Mr. W. Dundas: I believe that the principal factor which inspired the author to write his paper was that of fuel economy, and he has indicated a direction in which to look for improvements. The problem depends upon a number of conditions and circumstances, e.g. relative demands and capacity of boiler and power plant, coincidence of the demand for process steam and power load, stand-by plant, capital and labour costs, etc. I think that the author has rather underestimated his labour charges in the examples quoted. I have looked into the examples given in the paper, and in the case of the paper mill the whole of the power should be obtained from the process steam, that is, if the two supplies can co-operate, but evidently such is not the case as an additional 560 tons of coal is required to balance the power load, which corresponds to approximately 0·5 lb. per kWh and not 5·0 lb. as stated in the paper. Generally speaking, it is possible to effect a gain from 10 to 13 per cent on the total steam required. The two cases referred to on page 898 are instances where the combined plant is justifiable and every attempt should be made to conserve fuel, but that cannot be done at the expense of the electricity supply undertaking, which cannot reasonably be expected to give a stand-by supply at a very low rate. The minimum charge must cover at least the fixed charges on the capital cost involved in furnishing the supply.

Mr. W. J. Medlyn: I think that the author goes too far when he assumes that certain costs of upkeep and running of the electrical plant can be ignored, simply because a staff has to be provided in any case for the running of the steam plant. At the same time the elimination of actual waste is, of course, a very definite gain where this is found practicable. Take the case mentioned towards the end of page 897, for example. It is shown that 560 tons of coal are required for the electrical plant—just over 10 tons per week—but nothing is allowed for the labour of handling this nor for the extra cost of storage. Of course it may be a fact, as suggested by the author, that there is a surplus of labour employed on the steam plant, but that does not appear to be a sufficient reason for employing the surplus in other ways without a proper subdivision of the charges to be in agreement with the actual facts. Even if there is no way of economically using the surplus at the moment in any particular case, the manufacturing conditions vary from year to year. Then, again, it appears to be assumed in the paper that this valuable plant will practically run itself without any trained electrical staff, but with unskilled and untrained attendants in charge of the electrical plant I should expect costly and inconvenient breakdowns which might have a serious effect on the output of the works. Also I should not like to risk running an electrical plant without some supervision by a trained and competent electrical engineer. In those cases where electrical machinery is already installed these points are, of course, subject to modification, but they are not very definitely dealt with by the author. At the end of page 899 a case is quoted where the cost of generation is estimated at 1·21d. per unit, and at the beginning of the next page a public supply is stated to

be available at 1·25d. per unit. Apart from the criticisms already referred to, I suggest that with such a small margin this is clearly a case where the risks of the special installation should not be incurred. The cost of handling wood refuse is referred to, but in another part of the paper there is stated to be a market for saw-mill waste. It would be interesting to know what life of plant has been allowed for in the calculations. Until within comparatively recent years the Post Office had a number of small generating stations of capacities ranging from about 150 kW to 500 kW in London and the principal provincial towns. These installations were associated with heating systems and other services, and many of the economical side-lines advocated by the author were in operation. Owing to the importance of public requirements it was necessary to keep a good reserve of plant to ensure continuity of service, and the load factor was therefore poor. Of course, in manufacturing works, continuity of service is an important factor also, and a breakdown might result in serious loss. When most of our generating stations were erected (about 25 years ago) the possibility of a breakdown of the municipal supply was greater, and the comparative cost of energy much higher, than at the present time, and it has since proved to be an economical proposition to close the stations and take supplies in bulk from the supply undertakings. The quantity of energy taken, and the good day load, were factors which had a bearing on the question of the terms of supply. The valuable space rendered spare due to the withdrawal of the generating plant was also a matter of some importance. It is therefore evident that the case for steam-driven generating stations of about the capacities mentioned by the author cannot be supported so far as our experience goes.

Mr. G. A. Juhlin: I do not think it is possible to generalize on the question of individual power plants versus large central stations. Each case has to be considered on its merits because the importance of the various factors which determine whether it will be cheaper to purchase power than to install a generating plant must necessarily differ in each case. It must not be overlooked that there are some factors which cannot be easily assessed in monetary value, such as freedom from trouble associated with the running of a power plant, which fall on the shoulders of the supply undertaking when power is purchased. The author refers to the fact that more water power was utilized 40 to 50 years ago than to-day. I do not think this can be taken as any indication that there is less appreciation of economical considerations to-day than 50 years ago. The shutting down of the small individual water-driven mills is simply due to the growth of our large industrial centres, with better facilities for labour, transport, etc., which has made it possible to deliver the goods to the consumer at a lower price than could be done from the mills situated at points where water power was available. With regard to the small automatically-operated hydro-electric power plants in the United States to which reference is made in the paper, I believe that these are situated in districts where the cost of coal is very high, which makes it economically possible to pay the high capital charges involved in some of these hydro-electric stations and still compete with steam plants. Looking at this question from a domestic consumer's point of view, one cannot help feeling that if the whole coal cost were eliminated it would not materially affect the cost of lighting and power for household purposes, because the cost of the fuel is but a small fraction of the total cost. In connection with the burning of refuse from wood-working factories, I have seen several mills in Sweden where this was done and it is not uncommon to see coasting steamers burning the ends cut off planks and logs.

Mr. T. E. Herbert: The author makes one very good point, viz. that the correct thing to do in all these cases is to see that our coal supply is conserved, and he would like to see it made a penal offence for coal to be needlessly used. If it is a fact that any public supply undertaking uses its position to compel a man to take the whole of his supply from the public mains when he can get energy in another way by eliminating waste, such procedure appears to be wrong in principle. The value of having a perfectly reliable supply is very considerable, but there are cases where a small stand-by plant is absolutely essential. For example, in the case of a telephone exchange there should always be some method of getting the necessary electrical energy if something goes seriously wrong. Fortunately, the use of secondary batteries means that there are several hours available in which to make the necessary arrangements. One hopes that no serious disaster to the main power stations will happen, but arrangements have necessarily been made to avert such an emergency.

Mr. E. Rothwell: I thoroughly agree with the author's remarks regarding public institutions. I do not see how it is possible for a public supply to compete with a properly designed institutional central heating and power plant. When one considers that institutional requirements comprise heating, lighting and power continuously the whole year, night and day, it enables the coal to be used to provide all the necessary services with the utmost economy. The institution, for instance, in which I am interested has spent £56 000 in 7 years for fuel and gas, and it will be recognized that opportunities do arise to deal economically with the fuel question. The essential demand is heat and this has to be met by some means, either by separate domestic boilers or a complete central heating arrangement: also there are demands for steam for laundry purposes, hot water supplies, cooking, etc., and electrical energy simply becomes a by-product when exhaust steam can be utilized for most of the above requirements. I have devoted much study to this question and I certainly think that the title of the paper is very appropriate, particularly when one thinks for a moment of the enormous amount of heat thrown away daily in condensing plants. I know quite well that it is unavoidable in the majority of cases, but I do consider that every effort should be made by engineers to obtain the utmost from the coal that has to be burnt. This is not so in many cases. I am quite satisfied that where exhaust steam can be created by the generation of electrical energy and completely absorbed for useful heating services one can with confidence extend the application of electrical energy for all sorts of uses

and feel that every current-consuming device is utilizing the coal to the best advantage. It must also be remembered, as the author points out, that in every case boiler plant is necessary, even if a public supply is purchased, and when their maintenance cost is considered this makes the case for private plants beyond question, because under either arrangement the current-consuming appliances require a staff for their maintenance, and this staff is ample to supervise the generators.

Mr. J. Aylmer: The policy of the Electricity Commissioners is the rule which we should all follow, but there are exceptions to every rule, and we ought not to lose sight of this. As an electrical man I have felt very strongly in the past that it is one's duty to endorse the policy of the Commissioners, but when one comes across cases like those which have been mentioned, as an engineer one has to face facts. As a previous speaker has said, each case has to be considered on its merits, and these special cases which the author has put before us are indubitable. I consider he has been very fair: he has not given us, by any means, all the cases that he might have done, and I should have liked to hear the opinion of some of the engineers of the bigger combines in Manchester which run their own stations. Some concerns run their own plant, in spite of the objections mentioned by various speakers. I have in mind a case of a mill in the Manchester area which uses no steam at all for process work, but which has just put in a new set to replace an old one. From experience gained during the past 18 years they found that they could generate more cheaply themselves although using no process steam. Mr. Watson referred to a case where a supply undertaking quoted 1¼d. a unit for a supply. It would be interesting to know whether that was a small outlying station where the overhead charges for transmission and so on were heavy and had to be added on.

Mr. A. Tustin: In common with other speakers I believe that the method of making comparative estimates which the author has adopted is the correct one, in so far as he does not include in his cost of production of current any allowance for items such as boilers, which, though they are necessary for the production of electrical power, would have to be installed in any case, whether electrical power were generated or not. This question comes up in discussions from time to time and is never very satisfactorily dealt with. It seems to me that the right way to decide how a comparative estimate should be made up is to be clear in our minds, first of all, for what purpose the estimate is to be used. The right way to make up the estimate is the way which best fulfils its particular purpose. Any particular method may sometimes be right and sometimes wrong. Such an estimate as the one in the paper may be made by a private individual who is making up an estimate of the costs of various alternative possibilities with a view to enlarging his profit. What he wishes to know is, which of the two possible alternatives will actually, in point of fact, give him the biggest excess of income over expenditure in the future. It seems to me perfectly clear that from that point of view the author's method is the correct one, because, if one were to adopt the alternative method and distribute those costs "justly" between the two uses of the boiler plant, then the individual consumer concerned might actually adopt, on the basis of that estimate, a line of policy which will in fact give him less profit than he could otherwise obtain. That is not the kind of thing that private enterprise usually has in view. Secondly, an estimate may be made up from the point of view of public policy. There again it seems to me there can be no doubt that to leave out of the estimate all charges which are not *additional* charges caused by the development of the electricity supply is the right policy. In the particular example before us the omission of all charge for boiler plant in making up the estimate for the cost of production of power from process steam is giving the real economy of that proposal a chance to appear in the comparative figures. If such an estimate determines a user to install back-pressure plant, then it has been the means of securing the adoption of a policy which really does something to aid the conservation of public resources instead of leading to the development of two entirely separate sets of boiler plant where one would suffice. Thus, in spite of the criticisms which have been made of the author's system of making comparative estimates, which includes no charge for items of plant which would have to be installed in any case, we must conclude that his method is the right one. It is right for the private individual because it enables him to choose the alternative which really will make his profit a maximum, and it is also right from the social point of view because it causes the choice to be made which will give the maximum real economy of the nation's resources.

Mr. W. A. Christianson: I agree with previous speakers that each case should be considered on its merits, but I feel that where steam is required for process work or heating, a case can invariably be made out for an independent power plant, and frequently also where no process steam is required. Apart from the process steam case, air- and water-heating is a general requirement of every works and building of a public nature and offers a suitable field for an independent plant. As the factors affecting power and steam production costs have been more thoroughly appreciated, and the utilization of pass-out steam or exhaust from prime movers, coupled with economies from condensing, have been developed, the independent plant has fully met the competition of the public supply. This is evidenced by the amount of business being done by manufacturers of prime movers of all types and sizes which come within the range of "small power plants." As the size of installation increases, so does the case for the independent plant become stronger. Like the author, I have wondered why some works using process steam take a public supply, and I would suggest that a lack of appreciation of the possibilities of combining power and heating is the cause in some cases. I do not, however, agree as a general statement with the greater reliability of a public supply. The converse is just as likely to be the case. I heard of a works generating their own power—of quite a large amount—by steam engines and turbines working condensing and also using a large amount of heating steam direct from the boilers. Ultimately, however, the wastefulness of this arrangement was realized, and the power and heating com-

bined, with considerable resulting economy. I know also of two industrial concerns to-day each taking power from a large local undertaking whilst making their own steam for process work. They are now proposing to install their own generating plant to provide for their combined power and heating requirements. In addition to the economy to be gained, one of these concerns considers it a matter of importance to have its own power plant so as to have control in its own hands and avoid being " shut down " through a possible strike affecting the public supply over which it has no control. I believe that there are still a large number of plants in a similar position to the above in which a combination of power and heating requirements would be very advantageous. In cases where an independent plant is installed—and especially when this consists of one unit only—the public supply can with advantage be combined in the scheme to provide a complete or partial stand-by and also to meet the small night or week-end requirements which would not justify the running of the plant. I am in general agreement with the author, but I think that the figures of costs deserve further examination. Though the comments of previous speakers have been in the direction of inflating the figures quoted I should like to reduce one of these at least. The author gives the cost of a 650-kW geared pass-out turbo-generator set as £7 500. I believe that a plant of this character and size could be purchased and installed at the present day for £4 000 at the outside, or £5 000 including a condensing plant.

Mr. H. C. Crews: Small private plants relieve supply companies of their peak load, and I have in many cases been able to make agreements for an alternative supply where we have undertaken to avoid the peak load, unless advance arrangements were made with the supply undertaking on the telephone. This plan has worked very well. We have always been willing to take a sufficient number of units annually to make it a paying proposition for the supply undertaking. Where accumulators have worn out, instead of replating them we have in several cases connected the public supply. It is an advantage in many cases. Sometimes it is required to clean out the boilers, etc., and by arrangement the supply undertaking will take the whole load if they are in a position to supply. The author has referred to the way in which people are approached by supply undertakings. I should like to give an example of what occurs; it is very unfortunate that this is done occasionally. A prospective consumer is told that he can be supplied at, say, 0·3d. or 0·4d. plus a *small* fixed sum. At first that business man does not realize how this latter works out, but on investigation it is found that the fixed sum may perhaps be 0·9d., and that there are coal clauses which may mean an additional 0·1d. or 0·2d. When he has finally gone into the whole thing this business man is annoyed to find that the cost may work out to, say, 1·4d. per unit over all; and he thinks he has been deceived. It does the supply undertaking no good and sometimes it is too late to reconsider the matter. A great many public supply connections have been turned down for that reason; the business man thinks he has been deceived. Of course the crux of the whole question of private plant versus public supply is that every case must be considered on its merits. There are plenty of cases where a private plant does pay and pay very well. I am responsible for a number of supplies for public schools all over the country, and the majority have their own private plant. In four cases I have in mind, three have their own generating plant in duplicate. The fourth school, when their agreement ends with the supply undertaking, are going to install their own plant, because they can easily cover all capital costs on the same in five years' running, based on actual results of three similar cases. I have replaced private plants by public supply more often than the reverse, but in many cases private plants have been supplied and, taking into account every figure, have shown a saving. Local conditions decide the question entirely.

Mr. H. C. Lamb: As some speakers have already said, very often the question of private plant or public supply largely depends on the degree of importance which the power user attaches to reliability. The author gives two examples where people who might have used their own private plant have preferred to come on a public supply system. A hundred instances in Manchester could be given where chemical works, dyeing and finishing works, saw mills, paper mills, and so on, have preferred to come on the public supply, no doubt for sound reasons. It has been stated in the discussion that some supply undertakings refuse to give a supply of power to a consumer unless that consumer guarantees to take the whole of his power from them. There is certainly some misunderstanding here, and I do not think that any supply undertaking would attempt to make a rule of this kind Possibly there are special cases where it would be unprofitable to make an expensive extension to mains unless a definite load were guaranteed, and it is some such case, I think, which has given rise to the misunderstanding. There are many examples in Manchester of works driven partly by consumers' own plant, and partly from the Corporation's mains. It is not easy to check the author's figures. He speaks as an expert of matters with which he is familiar. Comment has been made on the small sum allowed in the paper for repairs, and it was suggested that the payments for insurance also covered repairs, but it is safe to say that no insurance company would insure and also carry out repairs for the trifling annual sum of £15. With regard to the operating figures on page 897, I notice that in the first case the coal is given as 560 tons, and the ash as 112 tons, that is to say, the ash removed is 20 per cent of the coal consumed. A coal with 20 per cent of ash, and the usual amount of moisture, will have a calorific value, as fired, of 10 500 B.Th.U. Allowing 1 050 B.Th.U. per lb. of steam, then to get 8 lb. of steam per lb. of coal, as the author does, means that these boiler houses are working, week in and week out, at an average efficiency of 80 per cent. We know from Mr. Brownlie's figures* that he tested 400 private plants and found that they had an average efficiency of 58 per cent. If anything like this obtained in the cases cited in the paper, the operating figures for coal (the principal cost) would have been considerably higher. The part of the paper dealing with process refuse is extremely

* See *Journal I.E.E.*, 1924, vol. 62, p. 385.

interesting. The author has given his views on the proper function of supply undertakings, whose duty apparently it is to give a temporary supply to suit the convenience of any consumer who wishes to take out his old plant and put in new. The public supply will then not be wanted again until the next emergency occurs. Of course a stand-by supply cannot be given without proper payment. The Electricity (Supply) Act of 1922 recognized this and absolved all supply undertakings from the obligation of giving a stand-by supply without a payment which would cover the fixed charges; and any supply undertaking will act as a stand-by on these terms. The author has given a good testimonial to the sales departments of the supply undertakings, but I do not know that they are really entitled to credit for any special wiliness, because it seems to me that a saw-mill owner's ordinary business keenness would put rather a different complexion upon the case. In this instance the author gives a figure of £845 as the annual cost of power generation by the saw-mill plant, but the balance sheet is not complete because he has not added the revenue which would have been obtained from the sale of the refuse, supposing it had not been consumed. He said that sawdust could be sold at 16s. per ton, and the works in question are making about 800 tons a year; so the sawdust alone would be worth something like £700 a year. If that be added to the £845, the total cost is far in excess of what it would have been if power had been obtained from a public supply. The author concludes by stating that a good case can be made out for the small plant. He says, "the capital outlay for super-power stations, long transmission lines, substations and the like, is very large, and this must introduce a heavy charge on to the cost per unit in scattered areas with a low load factor." It is quite true that the cost of super-power stations is "very large," but the important point is that the cost per kW for a large plant is far and away less than the cost per kW for a small plant. That is seen from the figures given in the paper. The cost per kW for a 25 000-kW turbo-alternator of the most expensive type, using high-pressure steam and high vacuum, is only about one quarter that of the small plants referred to in the paper. The fact is that a very large public station, with its high-tension mains and distributing stations can be put down at a lower capital cost than the small self-contained station. I feel strongly that the author is advocating a retrograde step when he suggests that there should be more small power stations. It does not seem desirable that we should have a forest of chimneys in our industrial towns, making it all the more difficult to tackle the smoke nuisance. Nor is it in the public interest to multiply small private power stations which must almost inevitably be much less efficient than the large station where the whole business of the operators is power production.

Mr. E. E. Baker (*communicated*): I should like to supplement the instances which the author has cited with results from other manufacturing firms who have been working for a considerable time with their own plant on a combined power and heating system. An undertaking in this country, which is probably one of the largest, consists of 8 000 b.h.p. in back-pressure steam dynamos at its various branches, the largest units being 500 kW. This is an undertaking which has been built up by degrees and was started many years ago, the programme being gradually to convert the works to a combined system, power and heat for the process work being generated in the same banks of boilers. There has been no difficulty in establishing a steam balance, the boiler plant has been reduced by as much as 40 per cent in some instances and the bulk of the electric supply, which was previously taken from an outside source, is now generated on the premises. The plant is all arranged on the unit system and a great deal of consideration has been given to arrive at the most simple and reliable plant for the purpose, with the result that a continuity of supply has been maintained with practically no stand-by plant and consequently with low capital expenditure. The results in fuel saving, cost per unit and improved process-steam distribution have more than justified the undertaking, which is still in the process of further development. Other instances show equally good results. A paper works is generating power at a cost lower than that at which a supply from an outside source could be obtained. A works manufacturing a speciality saved £1 200 in the first six months. A dye works, an institution and a public school are other instances taken at random where savings of £700, £2 000 and £200 respectively have resulted. Comparing the cost of production with that for any other scheme, the reason for the saving is so obvious that it is difficult to conceive any other result. In instances where steam balance presents any difficulty there should be a favourable opportunity for working in conjunction with a public supply, if one is available. Works will naturally install their own plant up to the extent of their demand for process steam, excess power being drawn from the public supply, the arrangement being automatic and controlled by the process-steam demand. The advantage of this system is that condensing, the weak link in the chain, is only employed in the large sets of public supply undertakings, where the sets can be run on good load factors with the minimum fuel consumption. At the present time many works install pass-out plant, which is another way of dealing with the steam balance question, though such firms would gladly buy any power in excess of that obtainable with their steam-heating demand if they could obtain it at a price which would pay them better than installing the pass-out plant. In connection with a pass-out plant it should be borne in mind that if the load factor on the low-pressure end and likewise the condensing plant is a poor one it involves a heavy capital expenditure, and a plant may not run with quite the best economy on purely condensing conditions when not passing out. But if, as Mr. Sills points out, the public supply undertaking is going to put all kinds of restrictions on consumers who have sound fuel-saving schemes, the advantages of such combinations will be lost and both the public supply undertaking and the consumer will be the sufferers, to say nothing of national interests as regards fuel economy. There is, of course, nothing new in the back-pressure engine; it has been working most economically on these lines for years, and the reason why it is now so prominent is the cost of fuel and

labour. Manufacturers want more power from fewer boilers and there is no other way of getting it, and as during the last two years one of the leading high-speed forced-lubrication engine manufacturers has turned out 130 engines operating on this system, totalling some 25 070 b.h.p., the public are obviously realizing the advantages of the proposals which the author has put before us.

Mr. R. A. Baldwin (*communicated*): The author has very rightly drawn attention to the publicity which is apt to lead the uninformed to suppose erroneously that it is from super-power stations that we are to obtain the cheapest possible supplies of electrical energy. It is to be regretted that there is not more general publicity given to the alternative sources which are set out in the paper, particularly among works managers and directors of industrial concerns. The fact that a super-power station with an overall thermal efficiency as high as 20 per cent is very unusual at present, and that the average overall efficiency of the public supply undertakings in Great Britain is only about 12 per cent, is obviously not appreciated. With a well-designed combined power and heating scheme it is easy to attain a thermal efficiency of 60 per cent on the plant, so that obviously the private plant must be justified in these cases unless the capital charges and wages for the small power plant more than outweigh the saving due to fuel costs, and of course there is no reason why they should. To the reasons which the author gives on page 899 for certain works taking a public electricity supply, when it is certain that by doing so they are wasting the national supplies of coal and increasing their own production costs, one might add the fact that the workers in many trades have been brought up to achieve results by rule-of-thumb methods, and they raise every possible objection to any apparent change in the process-steam supply. Numerous instances could be given of operatives raising objection to the use of steam which had passed through an engine, although it corresponded in every way to the supply previously obtained direct from the boilers through reducing valves, etc. The author has not included a reference to waste-heat boilers in his paper, but there is no doubt that by their use very cheap power could be generated in many works. In conjunction with steam-driven generating plant electrical energy can be produced at a cost which is practically the sum of capital charges, stores charges and wages for the plant. On gas-works, iron and steel works, cement works and similar places, electrical energy can be produced at a figure which is very much lower than the public supply rates.

Mr. C. J. Elliott (*communicated*): I am mainly interested in the author's remarks and figures in connection with bleach and dye works. The figure of 0·756d. per unit justifies the use of a small power plant for the case cited, as the cost of current, if purchased, would be in the neighbourhood of 0·9d. per unit for these conditions. An operating cost of 0·352d. per unit, whilst liberal, is near the mark, but the capital charges are excessive for the average case. If it is necessary to spend £2 000 on pipework, probably £1 500 should be spent as a work's improvement where the works are driven by small steam engines, and this amount would have to be spent if current were purchased from an outside source. The author's capital figure could therefore be legitimately reduced to a maximum of £5 000, and as the average life of the material represented by this amount would be in the neighbourhood of 35 years the interest and depreciation figure of 10 per cent could be reduced to, say, 8 per cent, which would make the total cost per unit 0·612d. The running plant should have a minimum life of 25 years, and this is confirmed by a set running under my supervision which is 26 years old and appears to be good for another 10 to 25 years' life. It was completely overhauled 12 months ago at a cost of £100, and tool marks were still visible in the cross-head guides. Experience gained with some 25 modern high-speed reciprocating sets working against back pressure, and 15 old electric lighting plants, has proved the supply given by them to be more reliable than the supplies taken at 10 works from outside sources. In very many cases there is a field for both the private plant and the outside supply in the one works. This would be mutually beneficial to both consumer and supply undertaking, but to get the full advantage of such a combination the supply undertaking will have to adopt a broader and more commercial spirit than that adopted by many of them at the present time.

Mr. A. C. Pain (*communicated*): Considering the matter on broad lines, it is difficult to understand how anyone can advocate a system which involves the deliberate waste of 60 per cent of the heat in the fuel burned by discharging it in the cooling water, as is the case in super-power and other condensing stations. Instead of trying to establish a monopoly for such a vicious system, surely the sensible course would be to encourage the private plants, or such of them as do make some attempt to avoid this serious waste by endeavouring to utilize the heat in the exhaust steam. Other countries are wise in this respect. Herr Treitel in his paper on "German Practice in Exhaust Steam Engineering" read before the First World Power Conference, after referring to the numerous industrial plants in that country which find that they can produce electrical energy at a lower cost by combining the production of power and heat, points out that this method of operation is very desirable from the point of view of national economy, and goes on to say that so far as Germany is concerned it is becoming the exception for power plant for industrial purposes to be of the ordinary condensing type. In other words, they are there fully alive to the iniquity of wasting the heat in the exhaust steam, and keen on finding ways and means of avoiding it. If a tithe of the thought and scheming which have been put into gaining half per cents in the thermal efficiency of large power stations had been devoted to reducing or avoiding the loss consequent upon the waste of heat in the cooling water, this country would be in a very much better position than it is at the present time. The way to do this is to seek out methods of utilizing the heat in the exhaust steam, and to encourage and assist the person or firm who is able and willing to do so, instead of placing obstacles in his way and endeavouring to force him to take his energy from the public supply mains. Facilities should be afforded for anyone who can generate current cheaply by the utilization of exhaust steam to

dispose of any surplus power into the public supply mains, by running in parallel with the public supply. This would have the effect of linking up the industrial power plants and enabling the industry which requires much steam and little power to collaborate with the industry which requires much power and little steam. It has sometimes been suggested that works which require much steam and little power should be located by the side of works which require much power and little steam, but if the power plants of such works were linked up in this way there would be no need for the works to be moved. This system is already in operation to a limited extent, notably the waste-heat stations on the North-East Coast and a few private plants, but it should be extended throughout the country. Its application need not be confined to waste steam, but to waste of all sorts, including those mentioned by the author; e.g. waste gases (coke-oven and blast-furnace); manufacturing wastes (household and town refuse); and last, but by no means least, waste water power, observing that there must be many small streams which could be economically utilized if this system prevailed, in addition to the few which are already being used. Is there any other industry which has such a waste as 60 per cent connected with its activities and which, like the power industry, makes no effort to amend it?

[The author's reply to this discussion will be found on page 911.]

Scottish Centre, at Dundee, 24 April, 1925.

Mr. A. P. Robertson: The author has endeavoured to show that in certain circumstances it would be better for a works to generate its own supply of electricity than to take it from a public supply undertaking. Whilst this possesses certain advantages, especially in process work, reliability and continuity of supply are worth something. If spare plant is to be installed the capital charges are greatly increased. The space required for the generating plant must also be carefully considered. In one case a firm valued this space at £10 000 for 500 kW and in this case decided to take a public supply. The space required for a substation and switchgear is not large compared with that required for generating plant inclusive of boilers. Where steam at low pressure is required for process work it is certainly economical to use an engine or prime mover as a reducing valve, and take advantage of the power generated. I do not, however, think that the author makes out a good case for the saw-mill on page 899. The gross cost per unit is given as 1·21d., and the public supply is available at 1·25d. per unit. Nothing has been allowed for handling the material to the boilers, and if this is included the cost would be 27 tons per week at 6d. per ton, equal to 13s. 6d. per week or £37 15s. per annum. This brings the cost per unit to 1·261d., which is higher than the cost of public supply. The author suggests a stand-by supply but does not make any allowance for this, the charge for which is £2 per annum per kW or £200 per annum for 100 kW. Add this to the gross cost of £845, and we get £1 045, equal to 1·494d. per unit. Taking the public supply at 1·25d. per unit, the yearly bill would be £875, showing a saving of £170 in favour of the public supply. In addition, there would be available about 600 tons of sawdust at 16s. per ton, equal to £480, and 200 tons of firewood at £1 per ton, equal to £200, a total of £680. Allowing 50 per cent for handling and selling (a very liberal figure) there would still be available £340 which, added to £170, gives £510 per annum in favour of the public supply. There still remain the long shooter shavings and the four-cutter dubbings, which would raise sufficient steam for canteen cooking, heating and seasoning. The space required for the boiler and engine would also be saved, and in a congested area this is a valuable asset. I have taken the author's figures and have excluded the handling of refuse in both cases. Even if the power were generated by wood-refuse gas plant as detailed on page 900 there would still be a saving in favour of taking a public supply. In an article on the raising of steam from waste products it was stated that sawdust and shavings were unsuitable for steam-raising if used alone, as a great deal of ash is produced which requires very frequent cleaning of the fires and ash-pits. The best way to burn sawdust and shavings is to mix them with cinders, coke breeze or other material. Chalk and sawdust have also been used. I should be glad if the author would say how he burns his sawdust. It is possible, of course, that owing to the percentage of wood chips and other solid matter the sawdust may burn easily in this case. Turning to small, self-contained power stations, whilst a small power station with up-to-date plant could possibly generate at less than 2d. per unit, there is no margin for spare plant, and arrangements would have to be made for a stand-by supply from a large power station. Supposing that mutual arrangements were in force whereby no stand-by charge was made, the fact of the small station requiring to be run in parallel with the larger units would necessitate more robust switchgear in the smaller station. The capital charges on this would add an appreciable amount to the unit cost, and although there might be certain cases where the situation of the small station would justify its erection, I am of the opinion that in the majority of cases the large super-power station can generate and distribute more cheaply. Before any small stations were erected, the circumstances would have to be taken into account for each individual case.

Mr. J. S. Thomson: In our area we have comparatively little experience of plants using process steam. The linen industry does use process steam, but when the details of the operation of such plants are investigated it is generally found that the amount of coal required to get the process steam is very much less than has been imagined. I think the real point is one of capital charges. If the consumer takes a supply from the public mains we know what happens if the supply fails, but if his own plant fails he suffers a couple of days' shut-down without much complaint. It is fairly safe to say that every factory with a private plant has stopped for two or three days at times, some of them more than once.

If, however, they come on to our mains and we stop, they immediately threaten to supply their own power. If they put in duplicate plant the cost would be very different. The author really arrives at his figures by making considerable use of the public supply, but whilst the principal object of a public supply undertaking is to do a public service, I do not think it is one of its aims to enable people to show what they can do with the supply undertaking's assistance and at the expense of other consumers. It is a very difficult subject; it is so easy to make out a case for anything. Taking my own company, for example, during the past 20 years only two consumers have gone off the mains, except, of course, those who have gone out of business altogether. One of these is, I know, very regretful that he did so, because he has already lost more money than would drive his works for years, and he is not finished yet. In the case of the ordinary simple self-contained station, there I think the question turns on two things, stand-by supply and load factor. Only last week I had an inquiry in respect to a 400-kW job. The applicant said that our prices were impossible, and in the course of the conversation it appeared that his argument was based on a 60 per cent load factor, whereas the load factor for the previous year was actually only 32½ per cent. On this basis his own figure was considerably higher than the figure we were offering, which was eventually accepted.

Mr. E. Seddon: In detailing the various items which make up the cost of the private plants, the author makes no allowance for buildings or spare plant, the inclusion of which would materially increase the capital costs of these small plants. When comparing these costs with the conditions obtained where a public supply is taken, some allowance should be made for the site value of the owner's plant. I submit that the author does not appear to have allowed a sufficient amount to cover wages for labour required in operating the various plants. The statement at the top of page 898 shows that other portions of the works are bearing certain costs for operation which should properly be allocated to the power plant. There is one class of power consumer which most central station engineers will agree is difficult to obtain as a consumer. I refer to a manufacturer who requires steam-heating for process work for such trades as papermaking, brewing, etc. Owners of private power plants do not as a rule put sufficient value on the reliability of energy supplied by the public authority. When private plants break down there is usually no alternative to closing the works until such time as the repairs are effected, whereas the chances of an interruption of public supply, except for a short period, are very remote, due to the fact that spare plant is held in reserve to meet emergencies. Fortunately for the whole community, private power plants with their attendant nuisance from smoke and dust are daily becoming fewer in number. Regarding the cheapest form of power, it is of course fully realized that each case must be worked out on its merits, as the cost of electricity varies so much as between different districts.

Mr. D. J. McDonald: Mr. Robertson has not stressed too highly the value of space, and I think that the paper does not give this point sufficient value. In any city space must be taken into account in every case in calculating the cost of generating the current. On the other hand, Mr. Robertson makes far too much of the stand-by plant. For that, however, not he, but the whole electrical engineering industry is to blame. When plants are put down the margin of power is in many cases far too small and the liability to breakdown far too great.

Prof. A. R. Fulton: There is no doubt that in certain circumstances small power plants can be used, but it is very doubtful whether they can successfully compete with the Dundee Corporation supply.

Mr. W. Sutcliffe: Experience has, I think, proved beyond dispute that in paper mills where a large quantity of process steam is required it is possible for a private plant to generate energy at considerably lower charges than could economically be offered by the nearest public supply undertaking. There are many successful examples of private plants in Scottish paper mills, and it is significant that at the moment there are to my knowledge three cases where such private plant is being installed. At the same time, however, many cases arise in which the demand for process steam is comparatively small; here the question as to whether a private plant should be installed depends very greatly on the prices that would have to be paid for current if purchased from outside. Power charges vary within wide limits in this country, certainly from 0·5d. to 2d. per unit, frequently depending on the views held by the local supply engineer. It is therefore obvious that what might be the correct thing to do in one district would be entirely wrong in another part of the country if the prices quoted in the two districts were low and high respectively. This point should be fully considered before coming to a decision regarding private plant versus public supply. Incidentally, I suggest that the wide discrepancy in supply charges for power throughout the country might be brought under review by the Electricity Commissioners, because at present we have the anomalous position that whilst manufacturers must compete in the price of their finished products, one of them, through no fault of his own, may have his operating costs made considerably higher than his rivals' owing to having to pay more for his power supply. The standardization of electricity charges, particularly for power purposes, is to my mind just as important as the standardization of frequency, and it is to be hoped that when the latter is accomplished the other will follow. Referring to the typical saw-mill installation cited by the author on page 899, my own view is that this particular example is not one which would warrant inclusion in the category of "Justifiable small power plants," because, according to the author's own showing, the difference of price in favour of the private plant amounts to 0·04d. per unit, or, assuming 168 000 units per annum, a matter of £28. I would suggest that it might have been preferable to have utilized the £3 600 capital expenditure on the plant in a better way by putting the money into the saw-mill business for development purposes, in which case presumably a return of anything between 10 and 15 per cent would have been shown. Assuming the minimum of 10 per cent return, the financial results would have been sufficient to turn the scales in favour of the public supply, unless the cost of handling and disposing of the refuse were considerably

higher than might be expected. It is probable, however, that in the near future our views regarding private as against public supply will undergo modification if the cost of energy falls to, say, ⅜d. per unit, even in the most remote hamlet, as a result of electrical developments consequent upon the proposed linking-up of the various supply stations throughout the country.

Mr. D. H. Bishop: In coming to a decision in any engineering problem a compromise has almost always to be made between some advantages and some disadvantages, and there are often factors whose value is difficult to express exactly in terms of money, e.g. convenience, saving in space, etc. We find that managers of works are in general very glad to rid themselves of the responsibility of generating plant. The cost of power is, after all, a comparatively small part of the total expense, and they naturally prefer to concentrate their time and energy on their own business, which is the more important part. Those of us who are intimately connected with power stations know what constant vigilance is required to keep the efficiency of the plant up to anything approaching the purchase guarantees, and I maintain that it is almost impossible to do it in the case of small works. A case may be made out on paper for a small power plant, but what really matters is not what the plant should do but what it actually will do in the course of years—a very different thing in practice. On the question of spare plant there is a difference of opinion. I am one of those who think that spare plant is necessary. I do not see how the efficiency of a modern, efficient plant can be kept up without an occasional overhaul. With the old, inefficient types it did not matter so much, but modern plants are much more delicate mechanisms, and not only fall in efficiency but may also actually refuse to go at all unless regular overhaul and adjustments are made, all of which take time. On page 897 the author mentions the way in which the case is put by the power supplier, but I suggest that the way in which the prospective power consumer states his case is equally important. We have found in a large number of cases which have changed over to a public supply that the units actually used and paid for are very much less than (sometimes only one third of) the amount the consumers said they would require. Their estimates of their costs per h.p.-hour were therefore greatly exaggerated. There are doubtless some cases in which a fair-minded engineer would agree that a private supply is advantageous, but only a few will come in this category.

Mr. A. B. Mallinson (*in reply*): This discussion has centred generally on (1) The general principles of small power stations as against super-power stations; (2) criticism of the capital and operating costs quoted; and (3) general comments on the various types of justifiable small power plant referred to in the paper, and I shall reply seriatim to the various points raised under those headings.

(1) *The general principles of small power stations as against the super-power station.*

Doubtless from the supply station engineer's point of view this paper is in general looked upon as "rank heresy," and I fully expected the storm of criticism from that source which arose in the discussion. There are, however, two sides from which the subject should be viewed; and in the paper I have endeavoured to show from the consumer's point of view how the source of supply of power can affect his individual industry. The other main point was national economy; the whole justification for the small power plant rests on these two factors, and particularly the latter.

There has been during the past two years far too much loose talk in the lay Press of super-power stations, which are going to make electric power available everywhere at such a price that industry will leap ahead, unemployment disappear, etc.

Several speakers, whilst agreeing that the small power station on waste-fuel or heat-economy lines is justified, have referred to the "straight power station" as being an indisputable case for the super-station. To be fair, however, the comparison should be made on the same basis, i.e. the super-power station prime mover of 1925 and the small power plant unit of the same period. To compare obsolescent small stations in which the units have steam consumptions of 15–40 lb. per kW is absurd. There is no difficulty in attaining a consumption of under 12 lb. per kW on sets of 2 000 kW to-day, and even on units of 100 kW a consumption of 15 lb. per kW is possible.

Messrs. Aylmer and Sills refer to the policy of the Electricity Commissioners as the rule we should all follow, and in general this is undoubtedly correct. The recommendations made by that technical body, however, when passed from one Government department to another, are liable to be used to force a line of action by a non-technical body, quite contrary to the national interests. The super-power station has undoubtedly a very large field to fill, but to apply its principle to all cases must mean that many manufacturers will pay far more for their power than would be the case had they produced it themselves.

Messrs. Watson and Lamb cite the fact that numerous works have taken a public supply when they used steam for process work as proof that the outside supply is the cheaper and better. My experience is that in the majority of such cases either (*a*) the works have never realized the potential source of cheap power that they have, or (*b*) that the limitation of capital expenditure has been the deciding factor.

Messrs. Watson, Medlyn, Lamb, Robertson, Thompson, Seddon and Bishop speak of the greater reliability of the public supply. Mr. Herbert, on the other hand, points out that in the case of telephone exchanges, where continuity of supply is essential, "fortunately, the use of secondary batteries means that there are several hours available in which to make the necessary arrangements." Undoubtedly power stations in general now give a very reliable supply, but it is doubtful if it can be said they are any better in this respect than a modern well-laid-out works power plant would be. Within a few days of this paper being read in Manchester, we had an example of the dislocation of operations in a town due to a power station breakdown. Many large manufacturers have instanced to me their desire to generate their own power purely and simply from the points of view of safeguarding continuity of opera-

tion, a factor of vital importance with the present trend of organized sympathetic strikes, etc. Mr. Christianson quotes similar examples.

Messrs. Watson, Robertson, Thompson, Seddon and Bishop raise the question of spare plant and compare the advantage of the public supply in this respect with the great risks undertaken in operating a small plant without such spares. As Mr. McDonald rightly points out, this is a very weak criticism. If one installs a mechanical drive in a factory, one does not put in a stand-by drive. Or, again, if one electrifies a works from the public supply, does one install a stand-by motor on each drive? Of course not! Why, therefore, if there is a dynamo between the engine in the one case and the motors in the other example, must there be a stand-by? Such arguments indicate little faith in the reliability of electrical plant.

Messrs. Clarke and Medlyn quote cases where advantages have been secured by shutting down small plants—there are thousands of such cases. The same remark applies to the power station; plants installed 15 to 25 years ago are not comparable with what is possible to-day.

Messrs. Lamb and Seddon speak of the nuisance which private plants, with their smoke and dust, are to the community; but there is no difficulty in operating the private plant with a clean stack. The paper mill quoted on page 897 burns some 600 tons of coal weekly with no sign of black smoke (there used to be plenty before the plant was modernized); whilst a colliery plant which I inspected last week, raising an average of 40 000 lb. of steam per hour, has a stack only 75 ft. high, and has been in use night and day for four years, yet the mortar in the stack courses is quite white up to the last ring of brickwork. The saw-mill case is quoted by the Medical Officer of Health in the district as an example of how refuse can be burnt without producing black smoke, one of the principal culprits being a similar works, operating on the public supply, who burn their refuse to get rid of it.

Messrs. Lamb and Thompson take me to task on the subject of stand-by supply. There is no question of getting anything without paying for it—surely the right way to look at these matters is from the national point of view. As Mr. Frith points out, often it is only by installing a public supply that a firm can remodel their layout and install a plant to produce their power from waste. Mr. Crews speaks of many cases where he has been able to arrange alternative supplies on the lines advocated.

The feeding back to the supply system of surplus power so generated is equally desirable, but can easily be so surrounded by difficulties in the way of complicated switchgear, etc., demanded by the supply undertaking that it becomes impossible; if approached in an open-minded manner there are appreciable developments possible in this direction. In numerous cases during the past few years the scheme has operated satisfactorily. The attitude sometimes taken up by supply undertakings with regard to firms generating part of their supply, has been criticized by the power station advocates, but my remarks in this respect are confirmed by Messrs. Sills and Baker, who have experienced the same difficulty.

(2) *Criticism of the capital and operating costs quoted.*

Capital cost.—Messrs. Watson, Tustin and Seddon challenge the non-inclusion of the capital cost of steam-raising plant in the heat-economy examples. Apparently they overlook the fact that the comparison is merely the cost per unit basis as against the cost of outside supply. If their view were right, one should equally add to public supply the proportionate charges on the capital outlay of the heating plant. Mr. Watson's suggestion that the boilers might equally have first been installed for power and then used for heating is doubtless correct in many cases, but we must consider the user's requirements as a whole. If he requires heat and power he cannot carry on with one alone, therefore if the outside supply cannot supply the steam for heating he must have his own steam-raising plant and then consider the power question separately.

Capital outlay.—The capital cost of the examples quoted has been criticized, Mr. Lamb stating that the capital outlay of the most expensive 25 000-kW turbo set was about one-quarter the price quoted in the paper. The average of the six cases given is £28·1 per kW. In the *Electrical Review* the cost of the new Ribble power station of 25 000 kW is given as £450 000, i.e. £18 per kW, plus £100 000 added for mains, or £22 per kW. Mr. Elliott points out that in the case of the dye works probably 25 per cent of the total outlay quoted would be a works improvement if this amount had to be spent to bring the present steam distribution system into line. This is no doubt correct; the case quoted was an extremely bad existing equipment. Mr. Christianson considers the amount allowed for the power plant in the case of the paper mill to be too high. The figures throughout the paper were purposely kept high to represent installed plant costs.

Labour.—Many speakers in the discussion consider the labour costs to be insufficient. The cases quoted (with one exception, the mental institution) are actual operating plants; in the case of the mental institution the estimated labour cost has since, as the result of inquiry, been further reduced.

The non-inclusion of labour cost for steam-raising on heat-economy plants is challenged by Messrs. Watson, Dundas and Seddon, but I cannot agree with their view. Either the cost of bought power must be compared with the cost at which it is possible to generate, or the comparison must be on a *thermal* basis pure and simple, the cost of bought power being added to the cost of steam-raising for heating. If this latter course were easy it would be the better way, but I fear that it would prove a shock to many manufacturers now on a public supply.

Trained staffs.—Mr. Medlyn speaks of the risk of operating without a trained electrical staff, but let us consider the evolution of the works-driving layout. In the old days with a mechanical drive an engine tender lubricated the engine by hand, the maintenance in general being in the hands of the works engineer. If motors were installed and a public supply taken, either the works engineer or a labourer looked after them, or, if the installation were sufficiently large, a works electrician. In any case the wages of such staff

do not affect the cost per unit of the public supply. If a firm generates its own power, surely the addition of one or two dynamos does not necessitate a trained staff. An up-to-date dynamo requires no more maintenance than an average motor.

Maintenance.—As Mr. Watson points out, the battery maintenance in the one case quoted had been omitted. This has now been added.

Insurances.—The insurances given in the paper were for boilers and engines, not motors, as they are common to both supplies.

Depreciation.—In reply to Mr. Medlyn, all the examples quoted have been worked out on the common basis of 10 per cent, i.e. 5 per cent interest and 5 per cent depreciation.

Local rates.—Mr. Watson refers to the lack of allowance for local rates. These were purposely not referred to in the tables given, because it is difficult to see how they would affect the case. To replace an old power plant with a new one is different from installing a new power plant as an extension to a power station existing solely for generating power. I am not aware that any reduction is made in the local rates if a works scraps its own power plant and purchases power.

(3) *General comments on the various types of justifiable small power plant described in the paper.*

(*a*) *Water.*—Mr. Watson's remarks on the possibilities of power in the flow of the Irwell as shown from the records taken are extremely interesting. This is just one of probably at least a hundred similar rivers available in this country.

I entirely agree with Mr. Frith in regard to the difficulties which arise in attempting to make use of water; sooner or later compulsory powers will have to be provided for this purpose.

(*b*) *Air.*—Since the paper was written there have been some interesting developments on the Continent in this respect. The new knowledge of the air forces attained in the perfection of the aeroplane, coupled with the development of automatic switchgear, undoubtedly open possibilities for interesting advance in this respect.

(*c*) *Heating and process steam.*—In the case of the paper mill, Mr. Medlyn refers to the fact that there is no provision in the operating costs for the handling of 560 tons of coal. This appears to be a great deal, but it is only about 2 per cent of the coal handled at the boiler-house of this mill. The coal is dumped by a wagon tipper and then elevated to the overhead bunker. At the most a few shillings would cover all the cost. Mr. Lamb, working from the ash figure, calculates the boiler efficiency to be 80 per cent, and compares that with Mr. Brownlie's figure of 58 per cent. Notwithstanding Mr. Brownlie's figures, I know at least two paper mills about this size in which the boiler efficiency with Lancashire boilers is regularly 74 per cent. Mr. Lamb's calculations are at fault in assuming that there is no combustible matter left in the 20 per cent ash. Actually the calorific value of the coal is 12 500–13 000 B.Th.U. The operating condition for the paper mill is 0·5 lb. not 5 lb. per kW as pointed out by Mr. Dundas.* He, however, has not grasped the need for the 560 tons of coal charged to power; it is not that the demand for power is greater than the demand for heating, but that a liberal allowance is made for steam which is lost by condensation, etc., in the prime mover and which is therefore not available for heating.

The remarks by Messrs. Baker, Baldwin, Elliott and Pain on the question of heat economy are much to the point. These gentlemen speak with practical experience of the operating results of such stations in all classes of industry, and whilst it might be said that some of them, being connected with the manufacture of engines, are biased, the same remark applies equally to the criticism of the various supply engineers.

Mr. Elliott's remarks, coming from one with considerable operating experience of back-pressure power plants, are extremely interesting. It will be noted that his comments on the capital and operating costs for the bleach and dye works are that the capital cost is too high and that the operating costs are near the mark but liberal.

As Messrs. Baldwin and Pain point out, there surely cannot be any case for argument when the power station average efficiency to-day is of the order of 12 to 20 per cent or so for the latest super-power station, yet a small heat-extraction station can run at 50 to 60 per cent efficiency.

I entirely agree with Mr. Pain's suggestion that private plants to operate on these lines should receive similar encouragement to the super-station; sooner or later the point will have to be dealt with. If a tithe of the expenditure now being incurred on many of the post-war so-called improvements were spent on such lines the improvement in the country's national operating efficiency would provide a handsome return.

Mr. Baldwin mentions the objection of workers to any change in their operating system. This is very often met with. Numerous cases have arisen of objections, for instance, to the direct use of exhaust steam for cooking; tact in introduction and a carefully thought-out layout are essential in the starting-up of such plants.

The public institution described by Mr. Rothwell is typically a case for a heat-extraction plant, yet it is somewhat surprising to find the Ministry of Health now look with disfavour on such equipments, presumably owing to pressure being put on them to support the public supply undertakings.

(*d*) *Power plants operating from process refuse.*—The principal case discussed is the typical saw-mill installation quoted on page 899. Mr. Watson, who knows the installation quoted, is in cordial agreement.

Messrs. Medlyn, Lamb and Robertson have endeavoured to show that this installation would far better have been left to operate from the public supply, the primary objections raised being:—

(i) That there is so little difference in the costs of generated and bought power.

(ii) That no allowance is made for the stand-by supply in the operating costs.

* This figure has since been corrected.

(iii) That no allowance is made for handling the refuse.
(iv) That if the public supply has been installed, the refuse could have been sold and additional revenue so obtained.

As it happens, this particular installation has been operating both ways. For a period of four years it was operating on the public supply, an old Lancashire boiler being retained to drive a small non-condensing engine of about 40 h.p. The boiler was fired with unsaleable waste refuse, helped out with coal if required. Since this plant has been put in it has been operating for 2½ years under the new system, with a 160-h.p. steam locomobile driving the bulk of the works, a 75-h.p. motor being retained direct on the town supply for a separate part of the works. The average actual operating results per year on the two systems are as follows:—

SAW-MILL OPERATING COSTS.

		4 years on public supply		2½ years on own supply
Bought electricity ..		£829		£444
Stand-by charges ..		—		66
Coal used in addition to wood refuse ..		171		—
Oil		26		35
Water		12		15
Labour (all engineering services for mills) ..		607		802
Insurances (boiler) ..		8		15
Maintenance		35		50
		£1 688		£1 427
Value of waste sold:—				
Firewood	£40		£93	
Sawdust	£523		£548	
		563		641
Net cost ..		£1 125		£786

It will be noted that when operating on public supply, owing to the inefficient way of burning the refuse, in addition to burning as fast as a man could fire, working hard all the time, a considerable amount of coal had to be bought. The value of refuse sold since the private plant was put in is greater than the refuse sold when the public supply was used. The only extra labour required has been the addition of an engine tender to look after the engine.

The figures for electricity include stand-by electricity, and are worked out on to-day's basis rate per unit. On page 899 the outlets through which this refuse can possibly be sold are indicated. There is only a limited demand for the bulk of the refuse produced, i.e. sawdust. Much of the refuse produced in wood manufacture is entirely unsaleable, and many works now operating on public supply have a boiler fired simply to get rid of this refuse, and make practically no use of the steam so raised. The handling of the refuse does not enter into the question; it is impossible to operate the mill without handling the refuse, whether the supply is public or private.

Mr. Robertson mentions the great amount of ash produced when burning wood refuse, and suggests that the best way is to mix it with cinders, coke or other material. My experience is that this is entirely wrong; there is remarkably little ash from burning straight wood refuse, and what there is is an excellent fertiliser, being specially suitable as a reviver for golf putting greens and grass lawns. To mix it with a hard fuel such as coke, breeze or cinders is most inadvisable. The whole secret of burning wood refuse lies in the design of the furnace; it is utterly impossible to do it in the ordinary fire-tube boiler or even in an extension furnace in front of it. The method employed in the plants quoted is to have a large underground step-grate furnace, where the refuse is fed in at the floor level, dries on the upper steps of the grate, and is then gradually pushed down into the fire zone and consumed, only the flames and hot gases passing through the boiler.

The grate area of the 160-h.p. plant quoted is 27 sq. ft., and the boiler pressure 174 lb. per sq. in.; the steam is superheated to a total temperature of 660° F.

(*e*) *Waste-heat boilers.*—Messrs. Frith and Baldwin comment on the manner in which power can be produced by waste-heat boilers. There have been many fine plants installed on these lines but, having no personal experience of them, I only lightly touched on the subject.

With regard to blast-furnace gases and gas engines or steam turbines, there are of course advocates for each method; my experience is that the apparently lower thermal efficiency of the boiler and turbine is more than counter-balanced by the greatly reduced maintenance and labour operating costs.

(*f*) *Household and town refuse.*—I agree with Mr. Watson that many of the installations installed in this country have been complete failures, but I would suggest that if such plants were re-developed on present-day lines, bearing in mind the various ways (apart from production of steam) in which such plants can produce revenue, there would be more done in that respect. In Germany there have been some very striking developments on these lines in the past few years.

(*g*) *Simple self-contained power stations.*—After carefully reading the remarks made by various speakers on this type of plant, I am more than ever convinced that there is a very strongly debatable case for the straight power station in many instances—either as a private plant, or as a public supply operating against the public power station. In the case of the private plant, such an installation can generally be installed to operate at a far better load factor than the average central station can hope for. Mr. Robertson speaks of a possibility of operating at about 2d. per unit; if such a figure were divided by 2 or 3 it would be nearer the figure which is actually being obtained.

For a small public supply station the bugbear of low load factor would doubtless apply, but, as already indicated in my reply, the developments in economy of small power units during the past few years have been remarkable, and it is quite impossible to make any comparison on plants dating back even a few years.

Finally, I would again emphasize the conclusions mentioned in the paper. If small power plants are to be successful, when being installed they must be regarded as one part of the complete operating equipment of the factory, with just the bare necessities required for producing the quantity of power called for, no elaboration on buildings, switchgear, duplicate plants and pipe lay-outs being allowed. In operation the plant should be given a chance to operate as it is designed to operate, i.e. with the minimum of attention. I would particularly draw attention to the remarks made by several speakers with regard to trained technical staff and the like. To go on these lines is courting failure. Prime movers as designed to-day will operate with the minimum of human attention, and there is absolutely no need, just because a dynamo is connected to the engine, to encourage the development of staffs on the lines of miniature central stations.

PROCEEDINGS OF THE INSTITUTION.

728TH ORDINARY MEETING, 19 MARCH, 1925.

(Held in the Institution Lecture Theatre.)

Mr. W. B. Woodhouse, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 5th March, 1925, were taken as read and were confirmed and signed.

Messrs. E. S. Ritter and E. S. Shoults were appointed scrutineers of the ballot for the election and transfer of members, and, at the end of the meeting, the result of the ballot was declared as follows:—

ELECTIONS.

Associate Members.

Bainbridge-Bell, Labouchere Hillyer, B.A.
Ball, Hereward Thomas S.
Blackman, Thomas Mainwaring.
Caldwell, Athol Ceadric A., B.E.
Hall, Eustace.
Ullrich, Edward Hill, B.A.

Graduates.

Bowler, Frank Colman, B.Sc.
Cameron, Alexander Robert, B.Sc.
Chambers, Edward Andrew.
Clarke, Albert Stanley.
Clarke, Arthur Roy.
Davies, Edward Gordon, B.Sc.
Goodier, William Richard.
Miller, David, B.Sc.
Minter, Robert William.
Murray, Ian Norman, B.Sc.
Parsons, Enoch Herbert.
Prickett, John Howard.
Sandys, George Henry.
Sard, Percy John.
Williams, Fred.

Students.

Adams, James Lewis M.
Anderson, Ernest William.
Anderson, John Rupert.
Andrews, Desmond.
Avery, Richard Leslie.
Baird, Robert William.
Barrett, Reginald James, B.A.
Bassett, Frederick Joseph.
Beaver, Roland Victor.
Bevan, Gilbert William.
Black, John Arthur.
Brassington, Edgar George.
Brooks, John.
Buckingham, Herbert Betts.

Students—continued.

Buckle, George William V.
Bullard, Horace Charles F.
Burdick, Robert Harry.
Calvert, Paul John.
Charlton, Walter Winlow.
Chatterjie, Hemen.
Cliff, James Stanley.
Coleman, Walter Robert.
Copeland, Robert.
Daniels, Frederic William.
David, Trevor.
Dorte, Philip Hoghton.
Dunn, Wilfrid Kenneth.
Edwards, Norman.
Eunson, John.
Evans, Frank.
Fitt, Cecil George.
Freeman, Charles Davis.
Gajjar, Harivaden Chimaulal.
Gerard-Boulton, Arthur.
Gillitt, Richard.
Gosland, Leslie.
Graham, John Aidan I.
Gray, Reginald Arthur G.
Grove, Peter Fayle, B.A.
Harbridge, Alfred James W.
Hart, Donald Alfred.
Heelis, Arthur James.
Hirons, John William.
Howarth, Sydney.
Howton, Sydney Charles.
Hunter, John.
Ife, Harold James.
Johnson, Percival Leigh.
Jolly, Thomas Herbert, R. H.
Jones, Howard Edward.
Keogh, Hubert Hedigan S.
Lambert, William.
Linley, Frank.
Lipscomb, Robert.
MacAlister, Alexander Frederick.
McDouall, Patrick Sutherland.
Mayes, Guy Noel H.
Metcalfe, Sidney.
Middleton, William John B.
Morris, Alfred James.
Morris, John Common.
Mountfort, Louis Vincent.
Moyes, John Edwin A.
Netherwood, Reginald.
Oddy, George Naylor.
Ord, Thomas Charles.
Osman, Abdelsalam Ahmed.
Palin, Frederick James.
Parrott, Thomas Henry.
Patel, Motilal Lallubhai.
Payne, Charles Ernest.
Peggs, Eric Percy G.
Rendle, Harold Barton.
Rickard-Smith, Hugh John.
Roynon, Frank Goodner.
Rushton, Eric, B.Sc.
Sabaretnam, Charles Victor W.
St. George, Reginald Graham.
Scott, Edward Chalmers.
Shackleton, Herbert.
Shaub, John Frederick H.
Smith, Frederick Wilce.

Students—continued.

Smith, Wilfrid Cyril.
Spiller, Richard Lucien.
Stirrat, James.
Strong, Albert Edward, B.Sc.(Eng.).
Thomson, George.
Tiffin, James Eynon.
Turner, Arthur Cecil.
Turner, John.
Webber, Francis Douglas.
Webber, William Rudston.
White, Kenneth.
Wilkinson, Kenneth James R.
Wimshurst, James Allan.
Wise, John Boles.
Young, Robert.

TRANSFERS.

Associate Member to Member.

Bartram, William Francis B.
Carey, Theophilus Mattingly.
Hughes, Aubrey Everard, M.C., B.Sc.(Eng.).
Kissel, Frederick Templeton M., B.Sc.
Macpherson, Hugh.
Parrott, Reginald George.

Graduate to Associate Member.

Francis, Thomas George, B.Sc.
Lucas, Herbert James.
Morcom, Herbert Geoffrey, B.Eng.

Student to Associate Member.

Harris, Valentine Arthur, B.Sc.Tech.
McVie, Allan, B.Sc.

Associate to Associate Member.

Johns, Morgan Jones.

Student to Graduate.

Allkins, Arthur Warrington.
Brown, Vance Auberon, B.Sc.Tech.
Charles, Edward Kay.
Damp, John William.
Daniel, Thomas Ernest, B.Eng.
Downing, Herbert Edward.
Ethelston, Simon, B.Sc.(Eng.).
Eversfield, Henry Thomas L.
Gibson, Henry Joseph, B.Sc.
Ginno, Sidney Charles.
Hambleton, Charles Ernest.
Hawkins, Raymond Cecil.
Mukherji, Debkinker, B.Sc., B.Eng.
Palmer, William Thomas, B.Sc.
Parr, Geoffrey.
Patrick, Ernest Reginald, Ph.D.
Petch, Herbert Stanley, B.Sc.(Eng.).
Pilkinton, Denis Fielden, B.Sc.Tech.
Smith, William Monro.
Spence, Harold Cruickshank.
Stahl, Henry Cecil.
Steele, William Herbert.
Ward, Mark, B.Sc.(Eng.).

The President: My next duty is a very pleasant one. We are here to-night to do honour to Sir Joseph Thomson by presenting to him the Faraday Medal of the Institution. Before making the formal presentation I shall ask Dr. Eccles to say something about the scientific work of Sir Joseph Thomson.

Dr. W. H. Eccles: This Institution has always been eager to acknowledge its debt to men of science, perhaps because many of its members have been devoted both to science and to engineering, or perhaps because application follows science more quickly in electrical than in any other branch of engineering. In our subject the theory of to-day becomes the practice of to-morrow, and in a few years the laboratory experiment becomes the essence of great industries, involving the expenditure of hundreds of thousands of pounds and affecting the well-being of millions of people. It is probably for all those reasons that the Council, in establishing the Faraday Medal, made it available not only to engineers but also to men of science. The name of Faraday in connection with this Medal has its significance. Faraday was a practical man in his manner of thinking. He insisted on visualizing electric and magnetic fields by forming a mental picture of lines of electric and of magnetic force which by their motion or their mere presence produced the various effects that have been collected into his theory of electricity and magnetism. I know that the Continental mathematicians and physicists sometimes gibe at the English method of thinking about abstract things by aid of a working model, but the fact is that the engineer, whether he be foreign or native, finds the conception of lines of force exceedingly useful and designs electrical machinery by aid of that conception. In due course, after Faraday, Maxwell produced his mathematical theory, and he was followed closely by J. J. Thomson, this year's recipient of the Medal. If we look at some of Thomson's writings of 30 years ago, and especially if we open the pages of his "Mathematical Elements of Electricity and Magnetism" on which many of us were nurtured electrically a generation ago, we can see that he was not only an interpreter of Maxwell but also a follower of Faraday, because throughout that book the conception of lines of force at rest and in motion is the keynote. After the "Mathematical Elements" came "Recent Researches," the most famous of all electrical books in the generation which followed Maxwell. These interpretations of Maxwell and of Faraday in the practical spirit which appeals so strongly to the electrical engineer might be enough to justify our Institution in conferring this medal upon Sir Joseph Thomson. But I think it is not only because he is a descendant of Faraday in the electrical sense that the Council thought of tendering him this honour. His original papers, spread over the past 30 years, have been so far-reaching, were so full of new calculations, new experiments and new speculations, that they have had profound effects on electrical thought, electrical practice and electrical discovery. "Discovery" I might define as the exploration of the unknown. We, as an Institution, are not interested in that directly. We are interested more in application and invention; but discovery is the raw material of invention and application. If there were no discovery in electrical science, then this Institution and the electrical industry would stagnate. The fact that Sir Joseph Thomson can rank as a great discoverer need not be elaborated. If I were asked to name only two or three of his great discoveries I should say that a principal one is his conception of electromagnetic mass—the electromagnetic inertia of a moving charge. That was the starting point of the revolution in electrical thought which culminated in

Einstein's work. Again, Sir Joseph was certainly the first to realize the importance of the electron, and, having realized it, he breathed into his students at the Cavendish Laboratory inspiration and energy which provoked the admiration of the world and produced another revolution of another kind in experimental physics. A further series of papers which excited very great attention some 20 years ago were those in which he showed how, from the electron theory of the atom, many of the chemical properties of matter can be deduced. I am leaving out quite a number of great conceptions, such as that of positive ray analysis; but I have mentioned those discoveries which I think will convince the members that in his fundamental work on the physics of the universe, J. J. Thomson has made himself an immortal name, which will splendidly sustain the lustre of the growing roll of Faraday Medallists.

The President: I think that it is fitting that I should say just a few words in regard to the Faraday Medal. The Faraday Medal of this Institution was founded in 1921 to commemorate the 50th anniversary of the first meeting of the Society of Telegraph Engineers. The Medal is awarded by the Council either for notable scientific or industrial achievement in electrical engineering, or for conspicuous service rendered to the advancement of electrical science, without restriction as to nationality, country of residence or membership of the Institution. The Medal has been awarded before to-night on three occasions—on the first occasion to the late Mr. Oliver Heaviside, on the second occasion to the Hon. Sir Charles Parsons, and on the third occasion to Dr. S. Z. de Ferranti. I now have very great pleasure in asking Sir Joseph Thomson to accept this Medal and this certificate commemorating the award.

The President then presented, in the name of the Institution, the Faraday Medal to Sir Joseph Thomson.

A paper by Mr. S. Evershed, Member, entitled "Permanent Magnets in Theory and Practice" (see page 725), was read and discussed and, on the motion of the President, a vote of thanks to the author was carried with acclamation. The meeting terminated at 7.55 p.m.

45TH MEETING OF THE WIRELESS SECTION, 1 APRIL, 1925.

(Held in the Institution Lecture Theatre.)

Mr. E. H. Shaughnessy, O.B.E., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 4th March, 1925, were taken as read and were confirmed and signed.

A paper by Major A. G. Lee, M.C., B.Sc., and Mr. A. J. Gill, B.Sc., Members, entitled "The Leafield Coupled Arc" (see page 697), was read and discussed.

On the motion of the Chairman a vote of thanks to the authors was carried with acclamation, and the meeting terminated at 7.35 p.m.

729TH ORDINARY MEETING, 2 APRIL, 1925.

(Held in the Institution Lecture Theatre.)

Mr. W. B. Woodhouse, President, took the chair at 6 p.m.

The minutes of the meeting of the 19th March, 1925, were taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

A list of donations to the Benevolent Fund (see page 423) was taken as read and the thanks of the meeting were accorded to the donors.

A paper by Messrs. G. Wilkinson, Member, and R. McCourt, entitled "Electricity Supply Tariffs: Their Simplification by Discrimination" (see page 850), and a paper by Mr. H. M. Sayers, Member, entitled "Electricity Supply Tariffs" (see page 845), were read and discussed.

On the motion of the President a hearty vote of thanks was accorded to the authors, and the meeting terminated at 7.55 p.m.

730TH ORDINARY MEETING, 23 APRIL, 1925.

(Held in the Institution Lecture Theatre.)

Mr. W. B. Woodhouse, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 2nd April, 1925, were taken as read and were confirmed and signed.

Messrs. T. A. St. Johnston and A. Travers were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the result of the ballot was declared as follows:—

ELECTIONS.

Members.

Greenham, George Frederick.
Mercer, Charles James.
Parker, William.

Associate Members.

Baker, Eustace Elwell.
Benjamin, Henri Lionel, B.E.
Boys, Geoffrey Vernon, B.A.
Clark, Richard Michael, B.Sc.(Eng.).
Edgeworth, Kenneth Essex, Lieut.-Col.
Fraser, Duncan Menzies, B.Sc.(Eng.).
Pasricha, Brij Lal.
Roe, William Bagley.
Shelley, Herbert John, B.Sc.
Watson, John Henry.

Graduates.

Aldis, Reginald Fred.
Ashton, Thomas James.
Brant, William.
Brown, Gilbert Alexander M.
Davies, Charles Morgan.
Dixon, Ernest George.
Drake, Robert Hamlyn M., B.A.
Finlay, James.
Foggo, John Johnston.
Graham, Robert Batthews.
Hanks, Harry.
Hughes, John Joseph.
King, Frank.
Lawrence, Robert.
McKinlay, Andrew.
March, Clifford.
Morgan, David Llewellyn.
Pickford, Harold Leslie.
Richardson, Ellis Matthew.
Taylor, Edward Abraham.
Turner, Wilfred Charles.
Wiggins, Ethel Reynell (Miss), B.A.
Winter, Harold.
Woodcock, Herbert William.
Wurm, George Louis.

Students.

Airey, Frank.
Barker, John.
Barker, Reginald Walter.
Barry, Frank Cecil N.
Bonsey, Thomas Harold Y.
Brackenburg, Charles Hereward, B.A.
Bucknall, John Thomas.
Bullimore, William Edward V.
Campbell, William Charlton.
Carter, John George.
Castle, James, B.Sc.(Eng.).
Chifferiel, Gerald Raymond.
Clayton, Gordon Albert.
Corfield, David Nisbett.
Croft, Hyla Bert.
Cullwick, Ernest Geoffrey.
D'Arcy, James.
de Ville, Stanley Halse.
Doig, Fergus Martin.
Donovan, Walter.
Elliot, Ernest Gerald S.
Embrey, Thomas James.
Ennis, Douglas Alexander.
Garratt, Stanley Reginald.
Green, Bertram Arthur.
Haley, George Bruce.
Honnor, Thomas Allwright D.
Hunt, Alan Porter.
Jackson, Sidney Bertram.
Jenner, Clifford George.
Johnstone, Hubert Trevor.
Keene, Vivian Vincent.
MacDonald, Ian Keith.
McNab, William Black.
Marshall, Frederick Geoffrey.
Martin, Norman Hadlow.

Students—continued.

Miller, John Morrison, B.A.
Mills, Arthur Kymer.
Moore, Ronald Frank.
Muscutt, John.
North, Howard Frederick.
Offord, William John.
Oliver-Bellasis, Richard, Lieut. R.N.
Paton, Stuart Henry, Lieut. R.N.
Pellow, Charles Henry.
Pierce, David Francis.
Range, James William.
Rissik, Hendrik.
Rudge, Frederick William.
Rutter, Gordon.
Sands, Philip Cooper.
Steward, Stanley Feargus.
Stuart, Peter Alexander R.
Towers, Herbert Cecil.
Turner, Harold.
Turner, Harold Mortson.
White, Henry George R.
Wilson, William Henry.
Wright, Frank Coram.
Wright, Frederick.
Yeo, Reginald Arthur.

TRANSFERS.

Associate Member to Member.

Binyon, Basil, O.B.E., M.A.
Cross, Edward.
Jones, Samuel Derwen.
Sparks, Algernon Charles.
Trencham, Henry.

Graduate to Associate Member.

Clough, Newsome Henry, B.Sc.(Eng.).
Fagge, Arthur Kenelm, B.Sc.(Eng.).
Gole, Sadashiv Mahadeo, B.Sc.
Horner, John Wood.
Newbery, Arthur Frederick.

Student to Associate Member.

Anderson, Norman Leonard, B.Sc.
Bolton, Leonard George, B.Sc.(Eng.).
Bradford, George, M.Eng.
Collard, John, B.Sc.(Eng.).
Harle, James Alfred, M.Sc.
Hasselt, Marc van.

Student to Graduate.

Bannister, Harold.
Birtwistle, Frank.
Cameron, Kenneth Albyn, B.Eng.
Cox, Percy Harold.
Dean, Harry Pitt, B.Sc.
Hunter, Norman.
Lambert, George Wrake.
Murray, John James L., B.Sc.(Eng.).
Puckle, Owen Standidge.
Robinson, Richard Edward.
Stephenson, Robert Maxwell, B.Sc.

Messrs. J. Coxon, P. Dunsheath and W. L. Wreford were appointed scrutineers of the ballot for the election of new Members of Council.

A paper by Messrs. K. G. Maxwell and Allan Monkhouse, Members, entitled "Recent Improvements in the Insulation of Electrical Machinery" was read and discussed.

On the motion of the President a vote of thanks to the authors was carried with acclamation, and the meeting terminated at 7.55 p.m.

THE MEASUREMENT OF FREQUENCY AND ALLIED QUANTITIES IN WIRELESS TELEGRAPHY.

By Lieut.-Col. K. E. Edgeworth, D.S.O., M.C., Royal Signals, and
G. W. N. Cobbold, M.A., late R.E., Associate Member.

(*Paper first received 11th November, and in final form 23rd December,* 1924; *read before the* Wireless Section *4th March,* 1925.)

Summary.

It has been customary during the past three decades to define the oscillation-frequencies of "wireless" in terms of the lengths, in metres and kilometres, of the corresponding ether waves.

During the past few years there has arisen a tendency to abandon the indirect definition and to state the frequencies themselves, in cycles per second or in kilocycles per second.

The paper suggests as a further alternative the description of frequencies in terms of "pitch," a term which is defined as a relationship of the particular frequency to some standard frequency.

The proposed standard is the frequency of 1 cycle per second, and the relationship suggested is such that the "pitch" is a logarithm of the ratio between these frequencies.

Some of the possible advantages of the use of "pitch" are described, and particular emphasis is laid on the advisability of employing it in the case of very short waves.

We owe a great debt of gratitude to the pioneers of electrical theory for the care with which they selected and defined the important fundamental units employed in all branches of electrical science. The same fundamental units provide the basis for all measurements in wireless telegraphy, but the very rapid development of this last-named science has necessitated considerable additions to existing nomenclature, and many new terms and units have sprung into existence. It is not surprising, therefore, that experience is showing that some of these new terms and units are not entirely convenient.

The employment of the expression "wave-length" to describe not only the actual wave-length of the disturbance in the ether but also the frequency of the corresponding oscillations which occur in closed circuits, was a natural development, but by no means a logical one. It is now being suggested that to measure frequency in cycles per second or kilocycles per second provides a more appropriate and convenient standard than to measure wave-lengths in metres or kilometres. It seems, therefore, to be a convenient opportunity for inquiring whether cycles per second and kilocycles per second really furnish the final and most appropriate solution, or whether other alternatives do not merit examination.

In this connection it is interesting to note that the problem of standardizing and comparing frequencies is a very old one, which reached a high degree of perfection in the art of music many centuries before wireless telegraphy was thought of. It seems worth while considering whether the new science of wireless telegraphy might not profit by the teachings of previous experience.

In the art of music it is not customary to compare notes of different pitch by means of frequency measurements in cycles and kilocycles per second. Their relationship is expressed in terms of the "interval" between them, which is measured in octaves or fractions of an octave, and the object of this paper is to suggest that, for the purpose of wireless telegraphy also, the octave may possibly be found more convenient than either the metre or the kilocycle per second. The subdivision of the octave into 1 000 parts which might appropriately be described as "milli-octaves" should provide all the accuracy which is likely to be required in practical work for many years to come.

If P denote the number which we have decided to measure in octaves, f the frequency in cycles per second, and K any arbitrary basic frequency, then these quantities are connected by the equation

$$f = K \times 2^P, \text{ or } P = \log_2 (f/K) \quad . \quad . \quad . \quad (1)$$

For the purpose of this paper it is necessary to give a name to the term P in the above equation, and it is proposed therefore to call P the "pitch" of the note.

It is perhaps fortunate that the art of music has never adopted an absolute standard of pitch, and it is therefore possible to make K unity in Equation (1), and thus to write :—

$$f = 2^P, \text{ or } P = \log_2 (f) \quad . \quad . \quad . \quad . \quad (2)$$

This equation defines an absolute scale of pitch.

For every point on the scale of frequency there is a corresponding point on the scale of wave-length, and Equation (2) defines a corresponding point on the scale of pitch.

Pianos are usually so tuned that the middle C has a frequency of 256 cycles per second, and the "pitch" of this note on the scale now proposed is therefore 8 octaves.

Passing to the frequencies in common use in wireless telegraphy, a frequency of 500 kilocycles per second, corresponding to a wave-length of 600 m, would have a pitch of 18·932, and existing practice would cover pitches from, say, 13 octaves (36 620 m) to 26 octaves (4·47 m).

Finally it may be noted that the pitch of the light waves which constitute the visible spectrum extends from about 48·5 to 49·6 octaves.

A system of reckoning which can include sound waves, wireless waves and light waves in terms of the same unit without requiring for the purpose more than five figures, seems to be deserving of serious consideration. At the same time the proposed system possesses important practical advantages over those now in use.

The following are the chief purposes for which units of wave-length, frequency or pitch are required :—

(i) The calibration of instruments (now commonly called wave-meters) by means of which each transmitter can be adjusted to the wave-length, frequency or pitch desired.

(ii) The allocation of selected wave-lengths, frequencies or pitches to particular transmitting stations.

Some wave-meters are so constructed that a switch enables the normal readings to be doubled. With such instruments, unless two scales are provided, the operator must make a mental calculation to interpret any reading on the higher scale.

If measurements of pitch are employed, no such complication arises. The two positions of the switch are marked 17 octaves and 18 octaves, or whatever it may be, and a single pointer indicates fractions of an octave on a single scale. Regarded as a "pitch-meter" the instrument reads from 17 octaves to 19 octaves on the absolute scale of pitch.

Strictly speaking, the instrument is neither a wave-meter nor a "pitch meter," but a frequency meter. The well-known relation connecting frequency and wave-length enables us, however, to graduate the scale in metres and to regard it as a wave-meter. In a similar manner, the relation between pitch and frequency defined by Equation (2) enables us to graduate the scale in octaves and to regard the instrument as a "pitch meter."

The allocation of frequencies to particular stations is usually governed by the need for avoiding interference, and the actual difference in frequency which must be provided for depends upon a number of different factors.

These factors belong to two types, the first involving an allowance of a certain fixed number of cycles per second, whilst in the second the allowance to be made is proportional to the frequency. The presence of side-bands due to the modulation in radio-telephony requires an allowance of the first type, but the other factors met with in wireless practice are usually of the second type.

It is evident that the importance of factors of the first type diminishes as the frequency increases, and that factors of this type can be neglected altogether in the case of very short waves. Under such conditions the employment of pitch rather than frequency simplifies the necessary calculations, because equal percentage differences of frequency are simply equivalent to equal increments of pitch. A change of 10 milli-octaves (0·010) in pitch is equivalent to a 0·71 per cent difference in frequency, a change of 30 milli-octaves (0·030) in pitch to a 2·1 per cent difference in frequency, and so on.

To take a practical example, suppose that it is desired to allot frequencies between 250 and 500 kilocycles per second with successive differences of 2 per cent and that the instrument available is graduated into 125 divisions, each of 2 kilocycles per second. Owing to the form in which the scale is necessarily subdivided, successive differences must be 6, 8 or 10 kilocycles per second, and it is impossible to avoid considerable departures from the desired 2 per cent difference in certain parts of the scale.

If, however, an instrument is graduated in octaves, 100 divisions will suffice and a change of pitch of 30 milli-octaves (0·030) will give the required result with absolute uniformity over the whole scale.

Recent work on wave-lengths below 100 m suggests that the use of such wave-lengths is likely to increase rapidly in the near future, and this fact lends additional weight to the above argument.

The authors would like to suggest that an absolute scale of pitch provides the most convenient method of defining frequencies over 3 000 kilocycles per second, i.e. of defining wave-lengths under 100 m, and they would urge that the method should receive the serious consideration of wireless engineers.

Discussion before the Wireless Section, 4 March, 1925.

Lieut.-Col. H. P. T. Lefroy: To estimate the practical value of the unit which the authors propose to introduce, its use should be considered from two different points of view, namely, (*a*) that of the user of radio apparatus, and (*b*) that of the designer of radio apparatus. As regards (*a*), a few years ago 100 m was about the minimum wave-length in normal use, whereas any wave-length down to about 1 m may now be used in practical radio communication. The band of frequencies available between 40 000 m and 100 m is only 1 per cent of the band available when wave-lengths down to 1 m are used, so that, for this and other well-known reasons, wave-lengths between 100 m and 1 m will be used for most of the future radio communication. It is felt by many of those who organize, control and operate radio communications that both wave-length and frequency are inconvenient units, for several reasons, particularly for wave-lengths between 100 m and 1 m: for them the new unit proposed by the authors has several advantages and should be given careful consideration. As regards (*b*), if the unit proposed by the authors is introduced, then no relation between that unit and the *CL* value of a circuit could be calculated without the use of logarithms, which would be very inconvenient, whereas, when using wave-length or frequency as units, the designer can now do such calculations without reference to tables. The authors' proposal would have more disadvantages than advantages for the designer of radio apparatus.

Captain T. G. Hodgkinson: The use of ratios to determine scale positions must appeal to all music lovers, although the audible frequencies occupy such a small portion of the known scale. The selection of one cycle per second as a unit gives lower frequencies than this negative "pitch," a point of interest to some people; engineers, however, are not so essentially concerned with frequency and wave-length as they are with the angular velocity of the periodic disturbance (I believe

that Prof. Perry first called it "speed"), and the unit "omega" (one radian per second) would make a very useful unit for the system of logarithmic division. The octave, however, has no exaggerated significance in radio work beyond the fact that it is frequently more prominent than other overtones, and the use of the common logarithm of the angular velocity rather than the logarithm to the base 2 of the frequency saves appreciable arithmetical work in the conversion of units. The use of the tenth harmonic in this way has all the advantages of the octave system outlined by the authors, and incidentally deals with the side-band type of allotment factor (by adding logarithms of consecutive whole numbers to the log of a velocity width, including the side-bands) as easily as with percentage difference factors. In the wave-meter problem it is not more difficult to add 0·3 to the mantissa of a logarithm than to add one to the characteristic in order to double the frequency of the authors' wave-meter, and the third decimal place gives a subdivision of 0·23 per cent. The logarithm of the angular velocity is an exceedingly useful figure to bear in mind, as it prevents slips in arithmetical work. The question of a name for such a logarithm does not arise, but a method of distinguishing between the common and Napierian logarithms would be to call the logarithm of 10 units of angular velocity one "Brigg," and do honour to a distinguished mathematician. Sub-audible velocities would range to 2·4 Briggs, audible velocities from 2·4 to 5, radio velocities from 5 to 9, visible light of the order of 15·5, and the velocity of the shortest gamma rays would be 20·726 Briggs.

Mr. R. V. Hansford: Although I should like to congratulate the authors on the ingenuity with which they have devised a new unit, I cannot see what advantages would follow its adoption. As regards the scale on a wave-meter, it is the type of the instrument which decides its utility, and the alteration of a scale of "wave-length" or "frequency" into an even scale of "pitch" will not improve the range or accuracy of the instrument, and to read in terms of an absolute scale of pitch would appear to be of no more value in practice than to read ordinary temperatures on an absolute scale of temperature. The authors speak of the mental calculation necessary in order to multiply by 2, but I should prefer this mental calculation to that of finding the voltage across a particular condenser when I was using 16 "pitches." The point I wish to make is that at some stage the use of frequency is essential. Therefore, why complicate matters by another unit which is merely a function of frequency? As regards the 2 per cent difference to which the authors refer towards the end of their paper, they assume that it will be desirable to calibrate from 250 to 500 kilocycles in successive differences of 2 per cent. I do not think we have any reason at present to suppose that the use of the higher frequencies will result in their allocation by percentage differences rather than arithmetical differences of kilocycles as at present. If it does so, one of the great anticipated advantages of the use of short waves will have been lost.

Major C. J. Aston: As the question of the use of wave-lengths, or cycles per second or pitch, is one which affects the user, I should like to appeal to the Press to inaugurate a discussion covering the whole world (including America, France, Germany, etc.) on this problem. It is not a matter which affects England only, or this Institution only. Previous speakers have referred to possible difficulties that will be introduced in the design of apparatus by the adoption of this system on account of the formulæ employing CL being no longer applicable. I think it will be generally agreed by designers that their skill and intelligence should be utilized for the benefit of users who are not so capable or accustomed to deal with formulæ as are designers. In my opinion the objections raised by designers are not of sufficient importance to outweigh any advantages which the proposed changes may have to the user. I would point out that with wave-lengths longer than about 300 m, i.e. with frequencies less than about 1 million per second, the absolute differences of frequency produced by telephony side-bands or required for heterodyne reception represent an appreciable percentage of the wave frequency, but that on shorter wave-lengths these side-band frequencies become of less and less importance, e.g. on 100 m wave-length a spectrum of 5 000 cycles per second is only 1/6th of 1 per cent of the wave frequency, and on 50 m wave-length it is only 1/12th of 1 per cent. It is necessary to separate channels of communication by more than these differences to allow for errors in the adjustment of apparatus and on account of the variations from the true wave-length that occur in practice. In my opinion, on wave-lengths of the order of 100 m or less the separation of channels of communication must be determined more by percentage difference than by absolute frequency difference, and any proposal which will render the use of percentage differences easier should receive most careful consideration, especially in view of the growing use of these wave-lengths at the present time. I think that Capt. Hodgkinson's alternative to the proposal made by the authors is a valuable one and I should like to see the two proposals given full publicity and their merits and objections discussed together.

Dr. R. L. Smith-Rose: One instance in which the use of a pitch scale has provided interesting results is in connection with the graphical representation of the performance of broadcasting receivers at audio frequencies. For example, the amplification curve of a stage comprising a valve with an intervalve transformer is usually plotted on a scale of uniform frequencies. On this scale the average characteristic obtained is approximately horizontal for about three-quarters of the width of the diagram. If, however, we attribute equal importance to all the notes on the pianoforte, the characteristic curve should be plotted on a scale of octaves with middle C at 256 cycles per second in the centre of the diagram. On such a scale the average transformer will be found to give a characteristic which is only straight for about one-quarter of the horizontal length of the diagram.

Mr. E. H. Shaughnessy: If we are talking of kilocycles we know that the difference between, say, 18·9 and 18·5 kilocycles is 0·4 of a kilocycle. I am not certain whether in the authors' method the difference between, say, 13 and 13·2 octaves is the same (reckon-

ing in cycles) as that between 18·7 octaves and 18·9 octaves. It is very convenient to reckon in terms of frequencies, and unless the proposed scale of octaves gives us the same easy mental facilities for calculating absolute frequency differences it does not offer any advantages over the present method.

Dr. E. T. Paris (*communicated*): The use of a logarithmic scale is almost a necessity in cases where measurements involve the consideration of wide ranges of wave-lengths and frequencies. The particular scale put forward by the authors appears to be capable of a very wide application to physical measurements, and its adoption for the calibration of wireless instruments seems to be desirable for several good reasons. There is something to be said, however, against the use of the word "pitch" as applied to the numbers obtained by taking the logarithm of the frequency to the base 2. In music and acoustics "pitch" has a well-established meaning, namely, the sensation which enables us to assign to sounds their relative positions on the musical scale. It is analogous, to some extent, to "colour" in the science of light, and to one accustomed to the use of "pitch" in the acoustical sense it would be as repugnant to speak of the "pitch" of a light wave as it would be to speak of the "colour" of a sound wave. In the generally accepted sense, in fact, "pitch" has no meaning when applied to light waves, since the ear is incapable of hearing vibrations of such high frequency. Would it not be better to find another name for the number $\log_2 (f)$, and thus avoid the confusion which is liable to arise with the acoustical meaning of "pitch"? It may be of interest to the authors to know that a somewhat similar logarithmic scale of pitch has been proposed for use in acoustical work by Harvey Fletcher (*Journal of the Franklin Institute*, 1923, vol. 196, p. 290). Fletcher defines pitch by the equation $p = 100 \log_2 (f)$. In this case the logarithm to the base 2 is not taken purely as a matter of convenience, but because the ear recognizes that notes separated by an octave are very similar sensations. Further, the factor 100 is used because the hundredth root of 2 is the average minimum interval by which two notes must be separated in order that they may be recognized by a normal ear as having different pitches. Hence a difference of unity in the pitch numbers of two notes means that they can just be discerned as giving separate pitch sensations. It will be seen that Fletcher's pitch scale has not been constructed without reference to our sense of pitch, but even then the use of the word "pitch" to describe the number P is not free from objection. The difficulty is, however, easily overcome by calling the numbers on Fletcher's scale "pitch numbers."

Lieut.-Col. K. E. Edgeworth and **Mr. G. W. N. Cobbold** (*in reply*): We should like to express our appreciation of the sympathetic reception which has been given to this paper on a controversial subject. It is natural that everyone should test the value of the proposed system by considering its application to his own work. Our view that the proposals put forward in the paper would benefit the user of wireless apparatus rather than the designer has been confirmed by the opinions expressed in the discussion.

We agree with Captain Hodgkinson that any logarithmic scale would possess the same practical advantages, but we contend that the scale suggested in the paper is more fundamental. The "user" does not have to enter into discussions involving the angular velocity of the periodic disturbance.

We think that Mr. Shaughnessy has not fully appreciated the difference between the two types of factor which govern the allotment of wave-lengths. The point is dealt with briefly in the paper and more fully by Major Aston in his remarks. A scale of pitch is not convenient for measuring definite differences of frequency such as 400 cycles, and a scale of kilocycles is equally inconvenient for measuring definite percentage differences.

We sympathize with Dr. Paris in his defence of vested interests and feel that we owe him an apology for trespass. A good deal of thought was devoted to the search for suitable terms, but nothing more suitable suggested itself.

In conclusion, we do not expect the proposed method of measurement to supersede existing methods, but we suggest that it possesses a sufficient field of usefulness to merit its adoption for particular purposes.

THE EFFECT OF WAVE DAMPING IN RADIO DIRECTION-FINDING.

By R. L. SMITH-ROSE, Ph.D., M.Sc., Associate Member.

[From the National Physical Laboratory; communicated by permission of the Radio Research Board.]

(*Paper received 3rd February, and read before the* WIRELESS SECTION *3rd June*, 1925.)

SUMMARY.

For the use of ships fitted with radio direction-finders, schemes for the provision of beacon transmitting-stations are being inaugurated in various parts of the world. In order to minimize interference it is evidently desirable that these beacons shall work on undamped or modulated undamped waves, and confidence in the accuracy of direction-finding when using these waves must accordingly be inspired in those who will make use of this application of wireless for navigation purposes. The present paper summarizes the hitherto published knowledge on the relative advantages of damped and undamped waves for accurate direction-finding, and then describes some special experiments which have been carried out in this country on this particular point. It is concluded that when direction-finding is employed at such times and under conditions which are known to produce the well-known "night effects" of variable errors in bearings and broad signal minima, these effects are equally likely on damped and undamped waves. Since the conditions under which direction-finding is accurate enough for marine navigation purposes at all times are now well known to be connected only with the distance of transmission over land and sea, it is to be inferred that the type of transmitted wave is immaterial to the accuracy, and that continuous waves, whether modulated or not, may in future be used with perfect confidence in all cases in which the damped waves from spark transmitters have given satisfactory results.

(1) PRELIMINARY.

At the present time the use of direction-finders operating upon the transmissions of radio stations is largely coming into use in its direct application as an aid to navigation. Many countries have now established collections of direction-finding stations for the use of both ships and aircraft, and in the mercantile shipping world the number of vessels which are equipped with direction-finders in addition to their ordinary wireless apparatus is increasing very rapidly. It is intended that, in part, these ship direction-finders shall operate on the ordinary coast transmitting-stations used for ship-and-shore communication, but, in addition, schemes are in being for the provision of suitable beacon transmitters, the sole function of which is to provide automatic and practically continuous transmission for the use of ships in their vicinity. In these days when the problem of restricting interference is one of the most acute in the art of radio communication, the possibility of these beacons employing "spark" transmitters is obviously viewed with some alarm. Yet among some of those responsible for navigation by wireless there is still a lack of confidence in the use of continuous waves, whether modulated or otherwise, as against damped waves, on account of the greater liability to error when employing the former type.

It will be advantageous, therefore, to examine all the available evidence on the use of continuous waves in direction-finding in order to understand if the reputed greater liability to errors is well-founded or otherwise. The subject was recently discussed briefly before the Wireless Section of this Institution,* but, as one speaker then stated, the matter was left in an unsatisfactory state, and the author will attempt in what follows to make his views on the subject quite clear.

(2) SUMMARY OF PREVIOUS KNOWLEDGE.

A. H. Taylor † appears to have been the first to publish, in 1919, systematic observations taken on both damped and continuous waves at Washington, U.S.A. Using continuous waves of length from 4·0 to 16·7 km, the variations recorded range from a few degrees in the daytime up to nearly 90° at night. It appeared to Taylor that, in general, the variations were greater on the longer than on the shorter waves, except where the transmission is over a comparatively short distance. For example, Annapolis (16·7 km, continuous waves) observed at Washington at a distance of 35 miles, practically over land, showed an extreme variation of 10°, whereas New Brunswick (13·6 km, continuous waves) at a distance of 175 miles showed nearly 90° variation. The only observations on spark transmissions referred to were made on the much shorter wave-lengths of 0·9 to 1·5 km, and in the case of Brooklyn on the latter wave-length a variation of 30° was recorded for a distance of transmission of about 250 miles, almost entirely over land. In view of the object of the present discussion it is considered interesting here to quote the concluding sentence of Taylor's paper. "The writer has no available data on continuous short-wave stations, but ventures to suggest that there is far more likelihood of serious deviations in the apparent bearings of such stations occurring than in the case of spark stations on similar wave-lengths."

* *Journal I.E.E.*, 1924, vol. 62, p. 701.

† A. H. TAYLOR: "Variation in Direction of Propagation of Long Electromagnetic Waves," Bureau of Standards, Scientific Paper No. 353, 1919.

In a paper summarizing a great deal of experience in direction-finding, Round * in 1920 mentioned the existence of variations at night, ranging up to 7° on "spark" signals and exceeding 30° on continuous-wave signals. Expression was given to the lack of evidence at that time showing any increase in the variation with wave-length, and the discussion on the paper indicated the somewhat hazy state of knowledge of these variable errors which then prevailed.

G. M. Wright † observed in 1920 that, in addition to "night effect" being more marked with undamped than with damped waves, its existence is indicated much more frequently in the latter case by the broadness of the signal minimum upon which the bearing is observed. The simultaneous occurrence of sharp minima and inaccurate bearings was considered to be very rare on damped-wave transmissions.

Further observations were published in 1920 by Kinsley and Sobey,‡ who made measurements on wave-lengths of 0·96 to 5·7 km from "spark" stations and 4·9 to 17·3 km on continuous waves. Variations in apparent bearings ranging up to 50° are recorded for distances of transmission of from 40 to 7 500 miles. The authors' experience indicated that undamped waves of great length show these variable effects much more frequently than damped waves of shorter length; but since the distance of transmission is usually very much greater in the former than in the latter case they express their conclusions on this matter as follows: "There does not seem to be any reason to believe that the short-wave sparks may not, under favourable conditions, show distortion (i.e. variations) of the same magnitude as that given by other types of transmitters." Several examples on both damped and undamped waves of failure to detect any signal minimum during a rotation of the direction-finding coil through 360° at certain periods of night variations, are given in the paper.

Pickard,§ in 1922, published some results taken on various American and two European stations, a feature of the results being that the bearings on the European stations at Otter Cliffs, Maine, U.S.A., showed a smaller average variation than those on the San Diego station. For example, the average variation of both day and night readings obtained during the month of August, 1921, was 2·1° on New Brunswick, 3·8° on Nauen, 4·2° on Bordeaux, 4·3° on Glace Bay, and 10·6° on San Diego. From the curves given in the paper it is seen that the average variation at night ranged up to about 12° for Nauen and Bordeaux, so that the individual variations must have been quite considerable. The chief feature of the difference in paths of transmissions from San Diego and from Europe to Otter Cliffs is that the former is entirely over land, whereas the latter is mostly over sea, except for the grazing incidence of the waves down the Atlantic coast of America.

* H. J. Round: "Direction and Position Finding," *Journal I.E.E.*, 1920, vol. 58, p. 229.

† G. M. Wright: "Direction Finding," *Year Book of Wireless Telegraphy and Telephony*, 1920, p. 946.

‡ C. Kinsley and A. Sobey: "Radio Direction-Changes and Variations of Audibility," *Proceedings of the Institute of Radio Engineers*, 1920, vol. 8, p. 299.

§ G. W. Pickard: "The Direction and Intensity of Waves from European Radiotelegraphic Stations," *Proceedings of the Institute of Radio Engineers*, 1922, vol. 10, p. 161.

Some observations made in France by Mesny * over a considerable period were published in 1922. These records showed that when using undamped waves of lengths 10 to 25 km the variations in apparent bearings at night ranged up to 90° for distances of transmission of 200 to 600 miles over land. No systematic error was evident in these cases, but when making similar observations on one of the American transmitting stations at a distance of about 4 000 miles, mostly over sea, a systematic error of 5° was found and the variations about this mean were confined to about 2·5°. Observations carried out on "spark" transmitting stations using damped waves of length 600 to 1 000 m resulted in only comparatively small errors of 10° or 15° at ranges of transmission of not less than 30 miles over land. In a large number of these cases it was found difficult to make any observation at all owing to the extremely flat minimum encountered at night. In the paper referred to, Mesny expresses the opinion that the difference in observed effects as described above was not due to the damping of the waves but to the difference in wave-lengths.

From the above brief résumé of previously published data it will be seen that there has hitherto been little opportunity of making any comparison between the relative effects of damped and undamped waves upon the errors and variations experienced on radio direction-finders. The only comparisons that have been carried out have been made between damped waves of short length (below 1·5 km) at short or medium ranges and undamped waves of great length (greater than 5·0 km) at comparatively long ranges, and at least two sets of experimenters have expressed the opinion that it was the difference in wave-length rather than the damping which was responsible for the varying results obtained. Since it is now known that the distance and also the nature of the path of transmission, whether sea or land, may affect the results, and also that, until recently, the shape of the transmitting aerial was suspected to have some influence,† it was evidently unfair to compare results obtained on damped waves from one station with those obtained on undamped waves from another station. For a strict comparison to be made it is essential for the waves to be as nearly as possible of the same length and to be emitted from the same aerial, and for the change from damped to undamped waves to be made as quickly as possible when observations are being carried out.

In his textbook published in 1922, Keen ‡ repeats the experience described by Wright that indefinite and distorted minima are more pronounced in connection with continuous waves than with damped waves, and that the presence of night-effect conditions can usually be recognized in the case of spark signals, since a sharp displaced minimum is exceedingly rare. The statement is made without any qualification as to the effects of wave-length, distance and nature of path of transmission, and is evidently meant to convey the

* R. Mesny: "The Variation in Direction and in Intensity of the Electromagnetic Field of a Wave," *L'Onde Electrique*, 1922, vol. 1, pp. 501 and 577.

† R. L. Smith-Rose: "The Effect of the Shape of the Transmitting Aerial upon Observed Bearings on a Radio Direction-Finder," *Journal I.E.E.*, 1924, vol. 62, p. 957.

‡ R. Keen: "Direction and Position Finding," 1922, p. 192.

impression that in the case of damped-wave transmission some warning of the existence of "night effect" with its possible varying errors is conveyed to the operator of the direction-finder, whereas in the case of undamped waves the minima are usually, if not always, quite sharp and serious errors in bearing may pass unnoticed. Keen has also pointed out * that such a result is to be expected if the theory of night errors put forward by T. L. Eckersley † is correct. It will be generally admitted, however, that it is experimental evidence, rather than deductions from a by no means universally accepted theory, which is required to settle a point of such vital interest to the future of wireless direction-finding.

(3) Recent Experiments.

In a paper ‡ published in 1922 the author described experiments which showed how errors might arise in the use of direction-finders on continuous-wave transmissions when the field from the local oscillator used for heterodyne purposes was allowed to interlink the receiving loop. The difficulties of adequately screening a valve oscillator were emphasized and the details of the design of a suitable screened oscillator were given. Oscillators of this type were employed at a number of direction-finding stations situated in Great Britain, engaged under the auspices of the Radio Research Board in the daily observation of the apparent bearings of many European transmitting stations. A large mass of data was collected during the years 1921–24, and the results of its analysis are being published in a series of official reports.*

(*a*) *Transmissions on long waves* (2 *to* 9 *km*).—During the first year of working the observations were confined to damped-wave transmission, whereas during the second year about 80 per cent of the total observations were made on undamped waves. The maximum variations recorded at each observing station were of the same order during the two years and ranged from 50° to 90°, the undamped-wave observations during the second year showing no marked difference from the damped-wave observations of the same or the previous year.

Among the relatively large mass of observations analysed in these reports, the only two transmitting stations which gave conditions approximating to the ideals mentioned above were Clifden and Karlsborg, and in Table 1 is given a summary of the whole year's observations obtained on these stations. The difference in wave-length in the case of the Karlsborg transmissions is known not to be responsible for any marked difference in the effects observed. It is seen from the table that although in some cases, both by day and by night, the extreme errors appear to be slightly

Table 1.

Summary of Observations made on Transmitting Stations using both Damped and Undamped Waves.

Transmitting station	Type of transmission and wave-length (km) *	Observing station	Day observations			Night observations		
			Number	Extreme Variation	Percentage more than 2° from mean	Number	Extreme Variation	Percentage more than 5° from mean
				deg.	per cent		deg.	per cent
Clifden	Spark (5·8)	Aberdeen	19	3·0	0·0	35	6·8	0·0
Clifden	C.W. (5·8)	Aberdeen	189	5·0	2·1	573	4·1	0·0
Clifden	Spark (5·8)	Bristol	19	0·7	0·0	32	6·2	0·0
Clifden	C.W. (5·8)	Bristol	166	5·6	1·0	212	3·9	0·0
Clifden	Spark (5·8)	Newcastle	85	1·5	0·0	66	12·5	9·1
Clifden	C.W. (5·8)	Newcastle	316	2·3	0·0	594	26·0	3·4
Clifden	Spark (5·8)	Teddington	34	1·5	0·0	62	15·7	14·5
Clifden	C.W. (5·8)	Teddington	153	5·7	4·6	389	38·5	9·8
Karlsborg	Spark (2·5)	Aberdeen	—	—	—	259	32·3	59·5
Karlsborg	C.W. (3·9)	Aberdeen	436	4·8	0·9	242	34·3	9·9
Karlsborg	Spark (2·5)	Bangor	32	2·8	0·0	257	34·4	28·4
Karlsborg	C.W. (3·9)	Bangor	540	10·8	7·6	291	51·1	19·2
Karlsborg	Spark (2·5)	Birmingham	136	5·8	11·7	438	47·5	25·8
Karlsborg	C.W. (3·9)	Birmingham	104	9·3	11·6	38	7·5	0·0
Karlsborg	Spark (2·5)	Bristol	27	5·2	3·7	324	41·0	21·6
Karlsborg	C.W. (3·9)	Bristol	84	2·5	0·0	23	11·9	8·7
Karlsborg	Spark (2·5)	Newcastle	171	6·6	20·5	485	57·5	42·5
Karlsborg	C.W. (3·9)	Newcastle	503	10·5	11·3	237	55·0	16·9

C.W. = continuous wave.

* *Loc. cit.*

† T. L. Eckersley: "The Effect of the Heaviside Layer on the Apparent Direction of Electromagnetic Waves," *Radio Review*, 1921, vol. 2, pp. 60 and 231.

‡ R. L. Smith-Rose: "On the Electromagnetic Screening of a Triode Oscillator," *Proceedings of the Physical Society of London*, 1922, vol. 34, p. 127.

* R. L. Smith-Rose: "Variations of Bearings of Radio Transmitting Stations," Radio Research Board, Special Report No. 2, 1924.

greater on undamped waves, the reverse is also true in other instances; and, particularly at night, the proportion of the errors is less on undamped than on damped waves. The actual differences tabulated are probably not significant and the deduction is therefore made that, provided the necessary precautions are taken with the direction-finding receiving apparatus as previously described, no difference in the ordinary night variations is experienced with the use of either damped or undamped waves of lengths within the range of 2 to 6 km. It may also be pointed out that in the case of the transmissions from Karlsborg to Aberdeen and Newcastle more than three-quarters of the path of transmission is over sea, whereas from the Clifden transmitting station the major portion of the path was over land.

(*b*) *Transmission on shorter waves* (750 *to* 1 800 *m*).—Between November 1923 and March 1924 a series of experiments was conducted, in which probably the closest possible approach to the ideal conditions mentioned in Section (2) was realized. For this purpose the transmitting station of the National Physical Laboratory, Teddington, was utilized, special signals being sent in turn on damped waves, interrupted continuous waves and continuous waves. The three types of transmission followed each other at regular intervals of two or three minutes, the whole cycle of transmissions being repeated every 10 minutes. Two direction-finding stations were employed at Orford and Slough respectively, and the experiments took the form of a series of simultaneous observations at the two stations over continuous periods of 24 hours at a time.

At the Slough station, distant only 11·5 miles from Teddington, no difference whatever could be detected in the bearings observed on either type of transmission by day or night. The maximum error in bearing observed throughout the whole series of tests was less than 2°, the great majority of the readings being correct to within 1°.

At Orford, distant 93 miles from Teddington, the observed bearings showed the usual effects associated with daylight and darkness. A summary of the results obtained in these tests is given in Table 2, in which no distinction is made between the day and night portions of the 24 hours.

By making an arbitrary division of the day and night periods at one hour after sunrise and one hour before sunset, the day observations are found to give a maximum error in bearing of less than 3°, and all the larger errors recorded above occurred during the night. It will be seen from the table that there is no obvious difference in the order of the variations experienced with either of the types of wave employed. In the last column is recorded the proportion of cases in which the signal minimum was so broad that no observation of bearing could be made. This proportion is seen to be quite an appreciable fraction of the total observations, particularly when it is remembered that the figure is considerably "diluted" by the daylight readings. While the exact percentage of readings giving such flat signal minima was found to be very variable in the different tests, it will be noted that there is a tendency for the continuous-wave transmission to give a maximum proportion and for the interrupted continuous waves to give a minimum proportion of such readings.

The above tests from Teddington to Orford were carried out at a distance over land for which previous experience has shown direction-finding to be of little use at night, on account of the variable errors and the ill-defined signal minima obtained. A consideration of all the results in Table 2, giving due weight to them in accordance with the number of complete 24-hour tests worked, tends to the deduction that the above differences in the results obtained are not very significant; the general conclusion being that all the usual types of night effect in direction-finding are equally likely to occur with either damped waves and with undamped waves, whether interrupted or not. The actual figures

TABLE 2.

Summary of Direction-Finding Observations made at Orford on Various Transmissions from Teddington.

(Distance = 93 miles; true bearing = 240·6°.)

Type of transmission and wave-length (m) *	Number of 24-hour periods worked	Total number of observations	Observed bearings: Extreme variation	Observed bearings: Percentage more than 2° from mean	Observed bearings: Percentage more than 5° from mean	Percentage of flat minima recorded
			deg.			
Spark (750)	3	418	20·0	1·8	0·8	11·5
I.C.W. (750)		299	17·0	1·4	1·0	7·0
C.W. (750)		388	20·0	5·0	2·5	25·7
Spark (1 000)	1	135	0·7	—	—	17·0
I.C.W. (1 000)		110	2·2	—	—	5·5
C.W. (1 000)		138	3·0	—	—	45·6†
Spark (1 800)	2	212	6·0	2·0	—	7·6
C.W. (1 800)		167	10·0	3·8	2·9	7·2

* C.W. = continuous waves; I.C.W. = interrupted continuous waves.
† In a subsequent test on this type of transmission the flat minima recorded were less than 15 per cent.

indicate that the type of effect known generally as broad or flat minimum is more common with undamped than with damped waves, but on account of the warning it gives to the operator this effect is not harmful in the application of direction-finding to navigation problems.

(4) CONCLUSIONS.

From careful, systematic observations carried out on various wave-lengths from 750 to 6 000 m it is concluded that the liability of wireless direction-finders to the type of errors known as "night effect" is equally great with damped and undamped waves. The special experiments were carried out with transmissions made directly over land, when it is common experience that these night-effects occur for ranges exceeding about 30 miles. Since, however, it has

already been shown * that when the path of transmission is entirely over sea and free from land and coastline effects, direction-finding with damped waves is accurate enough for most navigation purposes at distances up to 80–100 miles, it is inferred that equal reliability would be obtained with undamped waves. This is in direct confirmation of some experiments † carried out by the United States Lighthouse Service with radio beacons provided with modulated continuous-wave transmitters for the use of direction-finders on board ship. Comparative tests carried out with these and with the ordinary spark beacon transmitter showed that at various distances up to 132 miles over sea the accuracies were practically identical in each case, both by day and by night. The faith of the authorities in their results is exemplified by the fact that they are already introducing the modulated continuous-wave transmitters into their beacon stations.

* R. L. Smith-Rose: "Some Radio Direction-Finding Observations on Ship and Shore Transmitting Stations," *Journal I.E.E.*, 1924, vol. 62, p. 701.

† G. R. Putnam: "Radio Fog Signals for the Protection of Navigation: Recent Progress," *Proceedings of the National Academy of Sciences*, 1924, vol. 10, p. 211.

Discussion before the Wireless Section, 3 June, 1925.

Commander J. A. Slee: One specific purpose for which direction-finding is used is for the navigation of ships, and I wish to make a few remarks on this aspect of the matter. Either the ship can carry a direction-finder and take bearings of transmissions from known, fixed points, or the ship can do the transmitting and the direction-finder can be placed on land. In the present state of affairs there are a great many more ships with direction-finders than there are direction-finding stations on shore. At present the usual method —and I think from the seaman's point of view by far the best method—is for the ship to carry the direction-finder, so that when it comes to the navigation of ships the problem is to obtain accurate bearings in a ship from a fixed point. Experience shows that for most kinds of direction-finding, if the transmitting station, which is fixed, is any considerable distance inland, the bearings are poor. One must remember the conditions of navigation, however. It is not an academic study of the problems of direction-finding; an accurate bearing of a fixed point is what is required. The things which seamen are accustomed to deal with are headlands, lighthouses or similar fixed points on the coast, and they do not want bearings at long distances. I think it is safe to say that reliable bearings at 100 miles is the maximum requirement, and that in the great majority of cases 50 miles is quite enough. Thus the problem of direction-finding as applied to the navigation of ships is one of fairly short-distance work. The next point is to select transmitting stations which are suitable to the apparatus, viz. fairly short-wave stations situated on the coast—usually the 600-m stations used for communication with ships. The vast bulk of experience has been gained with these stations. It has been found that, due to the position of the land round the station, the existing coast stations have only comparatively small arcs in which bearings good enough for navigation can be taken. A demand has therefore arisen, and has just begun to be supplied, for special stations other than these stations for the purpose of assisting ships. The name which is being attached to this class of station in England is the "beacon" station. At present a wave-length of 1 000 m is being used, so we can state that from the point of view of navigation of ships a knowledge of the behaviour over moderate distances (all over water) of waves from 600 to 1 000 m is what is chiefly required. When ordinary spark transmitters are used their outstanding disadvantage is the amount of interference which they cause to other wireless services, and it is undoubtedly the object and the hope of everybody concerned with wireless to get that interference reduced. Against this it has been found that the reliability of the bearings taken from a spark station is of a high order. There is almost always a period between darkness and daylight when the bearings taken in a ship go wrong. The chances of error due to a bearing being taken during that period are small, because everybody knows the trouble and avoids it. If a bearing has to be used, it is used with great caution during those times. Once it is thoroughly dark it is very uncommon for the spark bearings to go wrong, but if they do so there is nearly always a great deterioration in the sharpness of the minima obtained, which gives warning of the temporary unreliability of the bearings. Thus the spark system has forced itself into a position of reliability and confidence among those concerned in the use of direction-finding for navigation. In order to get away from the interference difficulty, the problem of I.C.W. has been attacked, and as far as possible experiments have been made; but with ships which are actually at sea and using their direction-finders for navigation purposes the opportunity for academic experiment is not very great. The tendency is to show that at the moderate distances over which a ship requires bearings, I.C.W. behaves just the same as spark waves do. It is no worse and no less reliable, and the interference which it causes is undoubtedly considerably less. Therefore everybody concerned with the navigation of ships is perfectly content with the substitution of I.C.W. for spark. There remains the case of pure C.W. There is no very great amount of experience available, but what there is can be summarized in this way. For direction-finding purposes the ordinary form of direction-finder uses the familiar figure-of-eight diagram, but if that diagram is used during the hours of darkness it seems to be indisputable that pure C.W. bearings are very prone to wander. If the equally well-known heart-shaped diagram is used, then that wandering is a very great deal less, even if it does not entirely disappear. There remains the fact, however, that in ordinary practice it is very difficult in an iron ship, if not impossible, to get the polar curve of the heart-shaped diagram truly symmetrical. The result is that the two parts of the curve adjacent to the zero point are not alike, and the method of observa-

tion (which consists of taking two points of equal signal strength) will fail because those two points are not equally distant from the zero point, a resultant error of about 3 or 4 degrees remaining. I do not think it would be right to put it any lower than 3 degrees or higher than 5 degrees. The navigators of big ships nowadays have got into the habit of working to a higher degree of precision than this, and as a result I think I am right in saying that those using direction-finders for the navigation of ships at sea, although they would raise no objection to the introduction of I.C W. instead of spark for beacons, would all deplore the use of pure C.W. for beacons and for navigation as opposed to I.C.W. The I.C.W. stations at moderate ranges are quite satisfactory. At the longer ranges there is some evidence of I.C.W. wandering, but one cannot say that it is more so than in the case of spark, and for the case of ship navigation these longer ranges are not important. To put the matter in a nutshell, I think that, so far as the navigation of ships is concerned, the use of I.C.W. is perfectly suitable and satisfactory, and the amount of interference it is likely to cause to other services is not great. I do not think there is such a thing as a direction-finder at sea without a powerful amplifier attached to it, so the amount of power required to allow of accurate bearings being obtained at moderate distances (up to, say, 50 miles) is not very great. For instance, Trinity House has just started an experimental beacon station at Round Island, Scillies. First-class bearings at that place have been obtained at distances up to 100 miles. There is no question that that station is much more powerful than is necessary, and it has been blamed for interference, but it is clear that the power can be very considerably reduced.* At any rate, as far as Great Britain is concerned I think I am justified in saying that a station such as Round Island is the most powerful form of beacon station that can be wanted, and far less powerful stations will do all that is necessary further up the Channel and in narrower waters.

Dr. S. H. Long: The author has raised a very important question relative to direction-finding. It has long been the idea of many people employed on direction-finding work that C.W. and I.C.W. were of little use for such work. One can readily appreciate the advantages of C.W. or I.C.W. over spark if they could be used for direction-finding. This is especially the case in the present rapid advancement and progress in the art of direction-finding at sea, and in the development of radio-beacon stations in congested waters. I have been privileged to carry out a regular development of a system of direction-finding which has proved itself specially suitable for C.W. and I.C.W. work. Comparisons have been made with results on spark stations on wave-lengths used in mercantile radio communication, i.e. on wave-lengths of from about 450 m to 1 250 m. These tests have been carried out on transmission over both land and sea up to about 150 miles, and the general conclusions reached are that (*a*) the reliability of bearings on C.W. and I.C.W. is equal to that on spark; and (*b*) the working on C.W. or I.C.W. is preferable to and easier than that on spark, owing to the great selectivity and consequent lack of or diminution of jamming. Bearings can be taken on C.W. under conditions which entirely prohibit the taking of spark bearings. In regard to night effect, the results obtained at sea show that C.W. and I.C.W. are quite as reliable as spark by night. It has frequently been stated, as mentioned in the paper, that spark is more reliable than C.W., as the operator knows when "night-effect" is present, owing to the "woolly" indistinct minima. Our experience proves that this is not sound and that the trouble experienced is due not to the nature of the transmitted wave but to the type of reception used. In the system we have been developing, a compensating vertical aerial for sharpening up the minima in conjunction with a single rotating frame aerial is used. This compensating device operates on the set by means of a variable coupling, which changes with the angle of incidence of the wave-front on the receiver frame. With a vertical wave-front the coupling is extremely loose. When "night effect" is present the following phenomena are noticed: (1) The coupling between the rotating frame and the compensating vertical has to be tightened; (2) the bearings on C.W. can always be made sharp by the use of the coupling to the vertical aerial; (3) the C.W. bearings are very sharp when correct adjustment of coupling with the compensating vertical aerial is used, but these bearings in a few seconds tend to wander rapidly, i.e. if the true bearing is, say, 120°, in the course of 15 to 20 seconds one gets bearings of, say, 110°, 115°, 120° and 130°; and (4) the tightness of the coupling between the compensating vertical aerial and the rotating frame is an unfailing indication to the operator as to the reliability of bearings. Thus we see that although the direction-finding set cannot compensate for the refraction or reflection of the incoming wave, it at once indicates whether this refraction or reflection is present and warns the operator as to the correctness of the bearing read. This variation of coupling between compensating vertical aerial and rotating frame aerial when "night effect" is present seems to indicate a rapid changing in the slope of the wave-front relative to the rotating frame. This has been proved by using, in lieu of a rotating frame on a vertical axis and a compensating vertical aerial, a rotating frame on an axis which is also capable of rotation through about 60 degrees to the vertical. The greatest importance in the reception of C.W. lies not only in the choice of oscillator used but also in the method by which the oscillator is coupled into the receiving direction-finding system. Any system in which a secondary effect of the oscillator can occur is liable to produce errors, and the simplest system is that of a single rotating frame in which no secondary effects are possible. If more than one frame is used with the oscillator in the electrical centre of the frame and receiver, then complications are liable to arise, with consequent unreliability of bearings. Can the author give any information regarding the reliability of direction-finding on C.W., I.C.W. or spark systems of, say, 50 to 250 m wave-length? It

* This has now been done. At the moment good bearings are obtained at 40 to 50 miles.

is obvious that these are the wave-lengths to which great attention must be paid in the near future.

Mr. R. Keen : The paper summarizes very well the situation regarding the comparative reliability of spark, C.W. and modulated C.W., and it certainly seems that we are approaching the point at which we can say that we know roughly the limitations of the three systems of transmission. The evidence is still, however, a little conflicting. The author states that the only comparisons which have been made in the past regarding C.W. and spark have been made with damped waves at short distances and on short wave-lengths, as against C.W. on long waves and at great distances. Perhaps these are the only tests which have been published, but we must not forget the war experiences. The author refers to Round's paper, and in connection with the discussion on that paper he says that the knowledge of these variable errors seemed to be rather hazy at the time. Possibly that was the case, but the facts remain that many thousands —probably hundreds of thousands—of bearings were taken by very expert operators down our East Coast during the years 1915 to 1918, on both spark and C.W. stations from 1 800 m upwards and at distances of about 200 miles, mostly over sea. It is unfortunate that the whole of these readings could not have been analysed, but that was impossible at the time and we are obliged to rely on the impressions of those engaged on the work and those impressions were that the C.W. errors were very appreciably greater than the spark errors. What appears to me to be the most important point in the paper is contained in the concluding paragraph where the author infers that at distances up to 80 or 100 miles over sea, C.W. will be as reliable as spark. If this means that modulated C.W. is as reliable as spark, well and good, but in the summary which prefaces the paper pure C.W. is also included with modulated C.W. as being a type of transmission which can be used with perfect confidence wherever spark gives satisfactory results. Now, the opening words of the paper state that the purpose of all this work has been to get down to a reliable system of beacon working for ships and it seems to me that there is only one way in which we can ever find this out, namely by taking all our test-bearings from an iron ship at sea on beacon stations on shore of the power and type which will be used commercially. Such tests would prove costly but the results would be a final answer to all discussion on the subject. It is of the greatest interest to note that such tests have been carried out in America and that the results show that spark and modulated C.W. have approximately the same degree of reliability, but in view of the commercial interests involved and the extreme importance of the whole subject it seems not unreasonable to hope that the Radio Research Board will carry out some similar tests for purposes of confirmation. At the top of col. 2 on page 923 is a remark which is not quite clear to me. It is mentioned that the power necessary for a beacon station for the use of ships with crystal reception would have to be fairly high, but surely any ship having a direction-finder would also have valve reception. The author refers to my book and I agree with his remarks. My statement that errors on spark transmission nearly always give warning of their existence by indefinite minima, whilst C.W. bearings may be 30 or 40 degrees out and still have crisp minima, is to be taken generally as indicating the characteristics of the two types of transmission and may occur no matter what the wave-length or type of path may be. The author is a little sceptical regarding the Eckersley theory of the cause of night-effect errors, but it still remains the only theory which accounts in such a striking way for practically all the phenomena met with in direction-finding work. However, again I agree with the author that it is experimental evidence which is required, and this point cannot be emphasized too strongly. Although the information supplied by the Radio Research Board during the past two years has been extraordinarily interesting and valuable, I feel that this question of the reliability of C.W. and modulated C.W. beacons for ship direction-finding work can only be settled by further tests under working conditions, since direction-finding on a shore station and in a ship are totally different problems.

Major B. Binyon : In Section (1) of the paper the author refers to the serious interference which, in his opinion, would be incurred by the use of beacon stations operating on the spark system. I think, however, he overstates the case since such stations would not operate continuously, but only in thick weather, and then for a period of only 1 minute in every 10. Furthermore, the power employed by such transmitters need rarely exceed ½ kW, since the receivers used in conjunction with the ships' direction-finder sets would be highly sensitive, of the multi-valve type, and not crystal detectors as suggested in the paper. I am in agreement with Commander Slee that I.C.W. might be employed for beacon station work, though the plant is likely to be more costly. In considering the progress which will occur in marine development it is natural to suppose that the transition from the spark system to the C.W. system will be by the intermediate use of I.C.W. This transition, for financial reasons, must necessarily be gradual and it is therefore important, if we are to see progress in this direction, that there should be no technical reason why C.W. or I.C.W. cannot be exclusively used on board ship. It is most important, therefore, bearing in mind that ships may wish to take direction-finding bearings on one another—and this subject is altogether ignored in the paper—that the question of whether or no reliable bearings on C.W. can be obtained should be conclusively proved. In the author's conclusions he says: "Since, however, it has already been shown that when the path of transmission is entirely over sea and free from land and coastline effects, direction-finding with damped waves is accurate enough for most navigation purposes at distances up to 80–100 miles, it is inferred that equal reliability would be obtained with undamped waves." I do not think that this has been by any means proved by the author, nor that an inference of this character, on a subject so important, is justifiable. We have already experienced considerable difficulty in persuading the average mariner that direction-finding

on the damped-wave system is sufficiently accurate for navigation at sea, and I should be sorry if the progress of direction-finding were retarded by the establishment of C.W. beacons, unless it were conclusively proved that the same order of accuracy could be obtained therefrom as with the spark system. It is, however, admitted, as Commander Slee has stated, that reasonable accuracy may be expected on I.C.W. In connection with the wave-lengths on which experiments have been conducted and referred to in Table 2, it is unfortunate that these experiments could not have been made on the wave-lengths (spark, I.C.W. and C.W.) used by ships at sea, though one of these, viz. 1 000 m, is the wave-length proposed for use by beacon stations.

Mr. R. H. Barfield : When studying the paper I came to the conclusion that the lively controversy which existed before it was written was efficiently disposed of by the 10 000 (or so) observations contained in it, but I was apparently mistaken. In comparison with the mass of evidence contained in the paper my own experience is almost negligible, but I can testify that I have spent many hours by day and night taking observations of both damped and undamped waves, and I have never noticed any difference in the two classes as regards liability to errors.

Lieut.-Col. H. P. T. Lefroy : In this discussion, which deals with present methods of direction-finding, we should not lose sight of the fact that such methods are probably obsolescent and may be replaced by rotary beacons, with which the errors under discussion would not occur. Such beacons are analogous to rotating-beam lighthouses. Their range might be 50 miles, and I think, from what Commander Slee has said, that this will be sufficient. By arranging for one complete rotation in 72 seconds, and using a 1/10th second stop-watch in conjunction with the receiver, it should be possible to obtain the bearing of the transmitting beacon accurate to half a degree, and there should be no errors except those due to faulty observation. For various reasons, the radiation would be on wave-lengths shorter than 100 m, and I.C.W. would probably be used. As regards the ordinary systems in use at present, if I.C.W. is going to be used it is worth considering whether interruption could not be applied at the receiver instead of at the transmitter; in the latter case signals are heard as I.C.W. by those who are using them and also by those to whom they are causing interference, whilst in the former case they are heard as I.C.W. by those who are using them, but as C.W. by those who are not using a local interrupter with their receiver, so that less interference is caused. With properly designed apparatus the range, for a given C.W. input, is probably not less when interrupting at the receiver than when interrupting at the transmitter.

Admiral of the Fleet Sir H. B. Jackson : The discussion appears to have evinced the fact that spark and I.C.W. are equally to be depended upon. There is a certain amount of difference of opinion about C.W., but this may be due to the type of receiving station used. The author has carried out his experiments at well-tested stations where there were no local errors of any sort to be expected; whereas with those carried out in iron ships there are errors which are inherent in the station itself. Possibly the matter may be investigated by the Radio Research Board. Unfortunately the Board have not a ship at their disposal, but it is possible that they may think it necessary to obtain one for this purpose. At any rate I shall bring the matter to their notice.

Dr. R. L. Smith-Rose (*in reply*) : It is evident from the discussion that although a position of equality has been won for interrupted continuous-wave and damped wave transmission in wireless direction-finding, the question of its reliability in the case of continuous-wave transmission is still debatable. In regard to the latter case I must say that I see no reason to depart from the conclusions stated in the paper, for no satisfactory evidence has, in my opinion, been brought forward against them. Dr. Long's experience directly confirms my results and he is apparently satisfied as to the reliability of continuous-wave working over sea. Mr. Keen, on the other hand, has brought forward the only real evidence which has ever confronted me as to the greater liability to error of C.W. direction-finding, viz. that obtained during the years 1915–18. I would suggest, however, that the results of the investigations which it has been my privilege to conduct during the past five years are superior both in quantity and quality to those obtained during the above-mentioned period. They were begun with all the benefits of the experience of the preceding years, and were systematically planned and carried out under conditions free from the stress which necessarily accompanied the work done during the war. Furthermore, all the results obtained have been very carefully examined and co-ordinated and are now placed on record.

The real point which now remains at issue, however, has been made very clear by Commander Slee, Major Binyon and Mr. Keen. It is that although I have inferred that continuous-wave direction-finding is accurate over sea for distances up to 100 miles, there is no direct evidence for it; and the confidence of the mariner will not be obtained until the point has been proved. Owing to the very few ships fitted with undamped-wave transmitters no results for oversea working on C.W. were obtained during the experiments carried out at the Orford direction-finding station. The matter will obviously require the arrangement and carrying out of special experiments. It would appear to be desirable to make these experiments of a two-way nature, using one direction-finder on shore and one on a ship at sea; the ship and shore stations being also equipped with both spark and C.W. transmitters. Major Binyon has mentioned the additional desirability of carrying out tests between two ships. Constant tests would need to be carried out over a considerable period and the expense would naturally not be small.

Pending the carrying-out of such experiments it is to be hoped that the direction-finding services will be converted to I.C.W. working as soon as practicable. In this connection it is interesting to observe that confirmation of the reliability of modulated C.W. for direction-finding is afforded by the fact that the French authorities converted the radio-beacon at Cape Gris-Nez

from spark to modulated continuous-wave transmission as early as 1923.* In the paper referred to, it is stated that the results are quite as accurate as those obtained with damped-wave transmissions, and the remaining stations of the French radio-beacon service will shortly be converted in a similar manner.

Apart from the effect of wave-damping, Commander Slee mentions the variations in bearings observed when the path of the waves is along a coast or over land. I have recently become very interested in this phase of direction-finding, for although the experimental evidence is rapidly accumulating and is undeniable, the theoretical side of the subject is in a very unsatisfactory position. It is hoped to inaugurate some experiments to investigate this particular point in the near future. I have never experienced the twilight effect mentioned by Commander Slee, according to which the bearings are apt to be more unreliable in the neighbourhood of sunset than when total darkness prevails.

Dr. Long states that he uses a compensating vertical aerial for sharpening up the minimum, and also that the extent of the coupling of this aerial to the main receiving coil provides a means of detecting a change in the slope of the wave-front. Without practical experience of this particular arrangement I am loth to criticize; but I should like to draw attention to some recent experiments, the results of which show that owing to the

* A. Blondel: "Acoustic Selection in Radiogoniometry," *Comptes Rendus*, 1925, vol. 180, p. 1000.

high effective conductivity of the earth, the directions of the resultant electric and magnetic forces at the earth's surface due to a wave arriving at any angle of incidence are not seriously different from those obtained in the day-time with a single wave propagated horizontally.* On wave-lengths above 2 600 m the electric force never departs from the vertical by much more than 1°, and the magnetic force is always horizontal to within the same limit. In reply to Dr. Long's inquiry I regret that we have as yet no results to communicate as to direction-finding work on wave-lengths of 250 m and below.

I have to thank Mr. Keen and Major Binyon for drawing my attention to the paragraph referring to the use of crystal detectors. This was inserted in error and has now been deleted.

Colonel Lefroy has given us a reminder that there are systems of rotary beacon transmitters from which bearings may be obtained, and which may eventually supersede directional reception methods. At the present time I feel that the experimental evidence supporting the statement that these beacons should have no errors is somewhat small. It can be shown theoretically that one type of rotary beacon is liable to give errors under certain conditions, and it remains for the results of experiments to show how serious such errors may be.

* R. L. Smith-Rose and R. H. Barfield: "On the Determination of the Directions of the Forces in Wireless Waves at the Earth's Surface," *Proceedings of the Royal Society*, 1925, vol. 107, p. 587.

INSTITUTION NOTES.

Scholarships.

The following Scholarships have been awarded by the Council for 1925–1926:—

David Hughes Scholarship (value £50).

G. N. Peel, B.Sc. (Armstrong College, Newcastle-on-Tyne).

Salomons Scholarships (value £50 each).

R. O. Carter [City and Guilds (Engineering) College].
H. S. Leman (East London College).

National Certificates and Diplomas in Electrical Engineering.

The following schools have been approved under the scheme drawn up by the Board of Education and the Institution:—

Approved for Higher Grade Certificates (Advanced Part-time Course).

Leeds Central Technical School.
Leigh Municipal Technical School, Lancs.

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 July–25 August, 1925:—

	s.	d.
Anonymous	8	6
Beynon, J. H. (Swansea)	5	0
Clifford-Jones, E. T. (Colenso, Natal)	8	0
Hodgson, C. H. (Wolverhampton)	5	0
Jakeman, R. G. (Birmingham)	5	0*
Oliphant, T. (Shanghai)	15	0
Rogers, G. (Birmingham)	5	0*
Shires, G. E. (Doncaster)	8	6
Weaver, Horace G. (Newport, Mon.)	5	0

* Annual Subscriptions.

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2, Mining. (Section A.)
3, Petroleum. (Section B.)
4, Metallurgy of iron and steel. (Section C.)
5, Non-ferrous metallurgy. (Section D.)

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3, Indicating ammeters, voltmeters, wattmeters, frequency and power-factor meters.
4, Dry cells for telephone and similar purposes.
5, Electric cables, A, B and C classes (Rubber covered for telegraph and telephone purposes).
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2, Stationäre Ströme:
Stationäre elektr. Ströme v. F. Auerbach; Messappacate u. Messmethoden für stationäre Ströme v. W. Jaeger; Absolute Masse u. Einheiten v. W. Jaeger; Elektr. Konvektion v. A. Eichenwald; Elektr. Endosmose u. Strömungsströme v. M. Smoluchowski; Wärmeerzeugung d. elektr. Stromes v. O. Lummer; Elektrolyse u. elektrolyt. Polarisation v. G. v. Hevesy; Die Akkumulatoren v. G. v. Hevesy.
3, Elektronen u. Ionen:
Die Radioaktivität v. H. Geiger; Photo-elektrizität v. E. v. Schweidler; Atmospher. Elektrizität v. E. v. Schweidler u. K. W. F. Kohlrausch; Die Korpuskulare Strahlung in verdünnten Gasen v. E. Gehrcke; Die Ionisation der Gase v. R. Seeliger; Flammenleitung v. A. Becker; Lichtbogen v. E. Bräuer; Metall. Leitung v. J. Koenigsberger; Elektrolyt. Leitung v. L. Holborn; Leitung u. Ionisierung in verdünnten Gasen (Die Glimmentladung) v. G. Gehlhoff; Die Röntgenstrahlen v. P. Cermak.
4, Magnetismus u. Elektromagnetismus:
Magnetismus v. F. Auerbach; Magnetooptik v. W. Voigt; Magnetismus d. verschiedenen Stoffe- Elektromagnetismus-Erdmagnetismus-v. F. Auerbach; Elektrodynamik v. H. Diesselhorst.

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REPORT ON MEASUREMENTS MADE ON SIGNAL STRENGTH AT GREAT DISTANCES DURING 1922 AND 1923 BY AN EXPEDITION SENT TO AUSTRALIA.

By Captain H. J. ROUND, M.C., Member, T. L. ECKERSLEY, K. TREMELLEN and F. C. LUNNON, of Messrs. Marconi's Wireless Telegraph Co., Ltd.

(*Paper received 27th November, 1924, and read before the* WIRELESS SECTION *6th May,* 1925.)

PREFACE.

(By Captain H. J. Round, M.C.)

The first accurate wireless measurements of signal strength were made by Duddell and Taylor in 1905, and from 1909 to 1913 Austin and Cohen carried out a series of experiments over long distances from which they deduced their well-known formula.

In 1911-1912 the author and Mr. Tremellen carried out a fairly extensive series of measurements on daily and annual variations of high-power station signals at Chelmsford, and afterwards on various voyages. Practically all these tests were carried out with spark transmission.

In 1921 Vallauri published the first results on the use of the comparison method of measuring signals (originally suggested and used by Eccles for spark work).

The author, with Mr. Lunnon, just previous to this publication by Vallauri, had started developing a comparison method for measuring signals, differing in some particulars from that of Vallauri. Vallauri used two frame aerials at right angles, one pointed in the direction of signals and the other at right angles. The real signals on the one aerial were then compared by ear with artificial signals induced on the other one. We, however, used an artificial aerial instead of the aerial at right angles to the signal aerial.

Both methods have the serious fault that atmospherics are not of the same strength on the two systems, and Tremellen later on developed the "chip in" method, where the end of a message or a pause is waited for and, immediately transmission ceases, the artificial signal is induced in the real aerial. Whenever alternate dashes and spaces can be obtained from the transmitter it is of advantage.

A large number of preliminary experiments were carried out by Eckersley, Lunnon and Tremellen, to determine (*a*) errors of the instruments and (*b*) effective heights of aerials, and to get general experience in the use of the apparatus.

Continuous observations were then taken on various stations, first at Chelmsford (Broomfield), and then at various places in Great Britain.

Through the support of Mr. Alexanderson, a technical commission consisting of Mr. Beverage and Mr. Rust was sent to Brazil completely equipped with the measuring gear, to gather accurate data on European and American signals there. Here the first use of the instruments was made to determine the strength of atmospherics, the strength being defined as the E.M.F. required to be induced in the aerial in order to enable signals to be read at 20 words per minute.

This may be of questionable scientific value as a measurement, but is undoubtedly of great practical value, as it enables one to indicate how much stronger the transmitter must be to give a commercial service.

A further expedition to South Africa under Mr. L. D. Hill, again equipped with measuring gear, gave additional data.

We had, however, planned a much more extensive expedition which would give sufficient data on long waves to enable us to design stations for communication between any two places or to indicate whether such communication was beyond commercial possibilities.

Through the strong support of Mr. Godfrey Isaacs this bigger expedition was rendered possible, and Mr. Tremellen, accompanied by Mr. Allnutt, started on the 28th January, 1922, on the S.S. "Dorset," on a voyage to New Zealand, via Panama. The ship was fitted with the latest measuring apparatus and a large amount of auxiliary apparatus for direction-finding, etc. Our thanks are due to the owners, captain and officers of the S.S. "Dorset" of the Federal Shire Line for their invaluable aid during all these tests.

The gear was unshipped at New Zealand and sent to Australia, where the experiments were continued at Sydney, Melbourne (Koo-Wee-Rup) and Perth. The return voyage on the S.S. "Boonah" of the Australian Commonwealth Shipping Co. was chiefly eventful on account of Tremellen's development and tests of his theory of the source of atmospherics. We also wish to thank the owners, captain and officers of the S.S. "Boonah" of the Australian Commonwealth Shipping Co. for their invaluable aid.

Very great assistance was given to Mr. Tremellen in Australia by Mr. Fisk and the engineers of the Amalgamated Wireless Co. of Australasia, who have, since the expedition, carried out further extensive tests along similar lines.

The major portion of the theoretical work in this paper is due to Mr. T. L. Eckersley, and the preparation of the paper itself is the work of Mr. Eckersley and Mr. Tremellen.

A considerable amount of data will be published later, particularly that referring to the absolute readability of signals through atmospherics, this having been held back for commercial reasons.

THE MEASURING INSTRUMENT AND ITS CALIBRATION.

In order to give a fairly just idea of the accuracy to be expected in this work of signal measurement, it will not be out of place to give a brief description of the principles and details of the measuring instrument and its calibration. A fairly detailed description of the instrument has already been given before the Institution, and it will therefore be sufficient, for the sake of completeness, to indicate here, in as concise a manner as possible, the general principles, the accuracy of calibration and of the measurements, and the modifications which nearly two years' work with it have rendered possible or advisable.

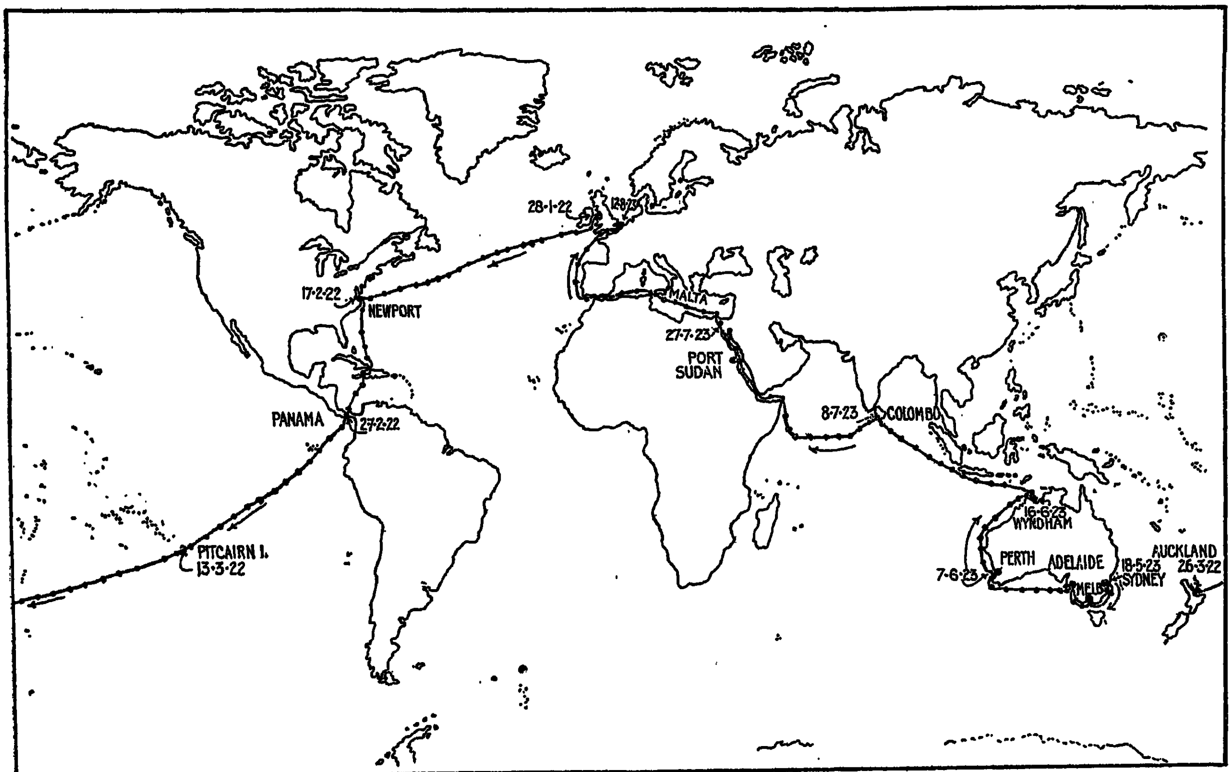
Signal measurement set.—The method consists essentially in providing an artificial continuous-wave signal (of the same frequency as the signal to be measured) the intensity of which can be varied over wide limits and measured with a fair degree of accuracy. This artificial signal can be introduced into the aerial or, alternatively, into a dummy circuit having the same electrical constants as the aerial, coupled to the receiving apparatus.

The strengths of the received signals in the dummy aerial caused by the artificial signal, and of those in the aerial caused by the incoming signal, are compared and equalized by varying the strength of the former. The calculated E.M.F. induced in the dummy or aerial by the former is then the same as that induced in the aerial by the signal.

The instrument therefore primarily measures the actual intensity of E.M.F. induced by the signal in the actual aerial used, but it is not a big step to infer from this the actual strength of the electric field in the incoming wave.

The artificial signals are supplied by an oscillator in a shielded box, coupled to an intermediate circuit in which the current can be accurately measured.

This intermediate circuit is coupled to the common part of the aerial and dummy circuit by means of a calibrated mutual inductance M, which is well shielded in a copper box. The R.M.S. electromotive force induced in the dummy circuit is then pMI, where I is the R.M.S. current in the intermediate circuit, and $p = 2\pi \times$ frequency.



Map showing the daily positions for the outward and homeward voyages.

Very perfect shielding is necessary to prevent any stray unmeasured E.M.F. from the oscillator being induced directly in the receiver. The whole scheme of connections is shown in Fig. 3, and Figs. 1 and 2 show views of the instrument itself.

The receiving apparatus, consisting of tuned circuit, amplifier and separate heterodyne, may be of any form suitable for receiving the particular signals required; all this apparatus should be preferably shielded in a metal box, for this helps to prevent any direct action of the signal on the amplifier.

The heterodyne signals should, if possible, be introduced into the last valve of the amplifier, as this ensures equality of effect on the dummy and aerial circuit signals.

With this apparatus it is possible to measure to about

10 per cent accuracy the actual E.M.F. induced in the receiving aerial by the incoming signals (under all but exceptional conditions of X's). By providing suitable coils, the instrument can be made to cover a wave-length range from about 400 m to 30 000 m.

The experience of the past two years has shown that it is nearly always possible to dispense with the dummy circuit and induce the homodyne signals directly into

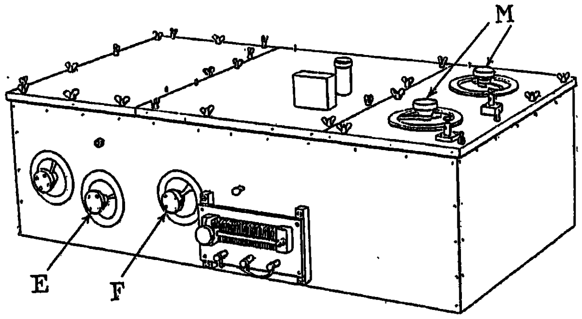


Fig. 1.

the aerial during the intervals when the transmitter is not sending. This procedure is certainly more accurate. In the first place it avoids the error consequent on the dummy circuit being not quite identical with the aerial; and it is difficult sometimes to ensure that the dummy circuit and aerial are even approximately the same. In the second place, when inducing direct into the aerial, the induced signal from the homodyne and

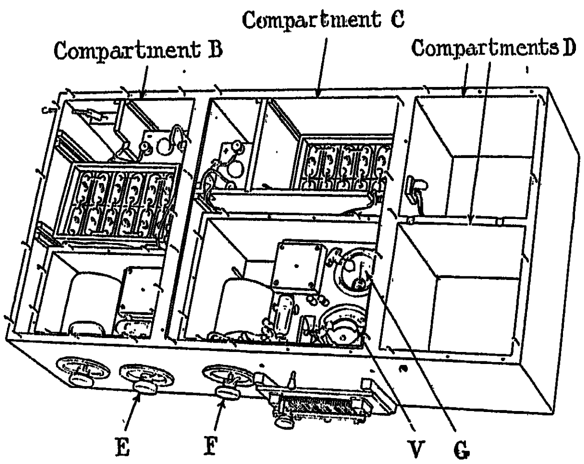


Fig. 2.

the incoming signals are under the same conditions as regards jamming and strays, which is a great advantage in matching the two accurately.

Calibration, capacity, mutual, effective height overall.—The aim or purpose of the instrument is to enable one to induce a *known* small E.M.F. in the common part of the aerial and dummy circuit (see Fig. 3) by means of the mutual inductance M. It is necessary then to know the E.M.F. induced in the secondary, i.e. pMI, where $p = 2\pi \times$ frequency, M is the mutual inductance, and I is the current in the primary of M, i.e. the intermediate circuit of the signal measurement instrument. The frequency is determined by ordinary wave-length methods (and can be compared accurately with any known standard). The current I is determined by measuring the maximum voltage across C, the intermediate circuit condenser, according to the relation $I_{max.} = CpV_{max.}$

$V_{max.}$ is measured by the potentiometer slide-back method already described by one of the authors (Captain Round) in the *Radio Review.*

Since there has been some doubt about the accuracy of the slide-back method of measuring high-frequency

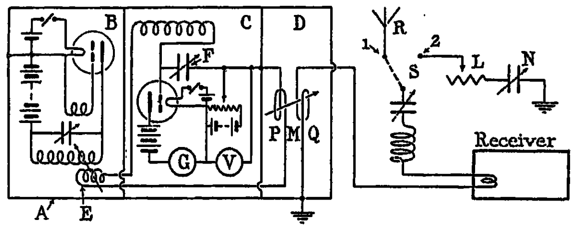


Fig. 3.

voltage,* we may refer here to a discussion of this measurement by Mr. Lunnon on page 304 of Volume 61 of the *Journal.* It would appear from the above that the measurement of pressures above 10 volts is accurate to about 5 per cent, and that by making a constant known correction for each valve the accuracy will probably be quite sufficient for the purposes required. These considerations are further checked by an overall calibration of the measuring instrument, involving of course the signal voltage measurement. This checks within the limits of the experimental errors.

The capacity C is determined by substituting a known, calibrated, variable air condenser. In general it is

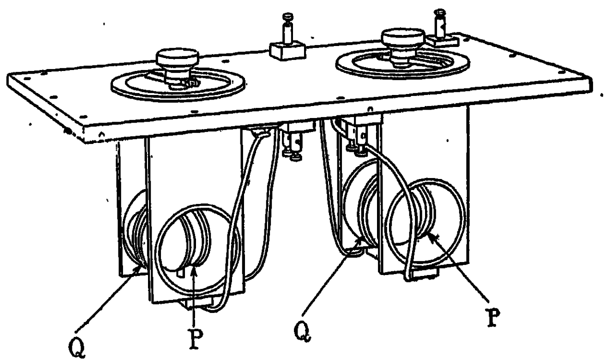


Fig. 4.

arranged that C shall be relatively large in any measurement, so that stray capacities can be neglected.

The mutual inductance M was measured at low frequencies by comparison with a known, standard mutual inductance (Campbell patent type) and checked at higher frequencies by another method. It was possible to neglect the effect of mutual capacity between the primary and secondary, since in all cases the primary of M formed only a very small fraction of the self-inductance of the intermediate circuit. Mutual inductances covering two ranges are shown in Fig. 4.

* E. B. Moullin: *Journal I.E.E.*, 1923, vol. 61, p. 295.

In terms of the known quantities the E.M.F. induced in the aerial could be calculated from the formula:

$$E = \frac{2\,515\, MCV}{\lambda^2}$$

where M is in microhenrys, V is in volts, C is in microfarads, and λ is the wave-length in metres.

This gives the E.M.F. induced in the dummy circuit or aerial, which is made equal to the E.M.F. induced by the signal in the aerial (V say).

In order to infer the amplitude of the field of the wave, the effective height of the aerial must be known. For if E is the voltage per cm in the wave and h is the effective height in cm, then Eh = total voltage induced by the signal in the aerial, i.e. V, or $E = V/h$.

Effective heights.—The quantity we wish to measure is, by definition, the ratio between the actual voltage induced in the aerial, which can be measured directly by means of the signal measurement instrument, and the actual field strength E, in volts per metre say, in the wave-front. Perhaps the most satisfactory way, theoretically, is to measure E actually by means of a frame and compare it with a simultaneous measurement of V, the total voltage induced in the aerial.

There is little doubt that, within the accuracy required, the field strength E can be deduced from voltage measurements made with a frame, when the frame dimensions are known and when suitable precautions are taken. The relation between V and E is then $V = 2\pi AE/\lambda$, where A is the area of the frame and λ is the wave-length.

The other method is to produce a known value of E by means of a second transmitting aerial situated some little distance away, sending with a known current from an aerial of known effective height. Apart from the last difficulty, we are dependent in this case upon an accurate knowledge of the transmission formula for transmission over semi-conducting earth. This knowledge is, as far as the authors are aware, lacking up to the present, so that any experiment depending upon this method must be considered to be inaccurate to an extent proportional to the inaccuracy of the transmission formula used. The correct method is doubtless the former, and would be universally used were it not that it is a particularly difficult measurement to make. The difficulty lies in the fact that it is almost impossible to ensure that the voltage measured is that induced in the frame and that no difference of potential between the frame and earth is included in the measured value of V.

A very symmetrical circuit must be arranged to ensure that this " vertical component " is balanced out. With regard to the second method, which involves the transmission formula, no difficulty is experienced if we assume that the earth is perfectly conducting, for in this case we know definitely from the work of Hertz that the E.M.F. can be calculated with sufficient accuracy from the formula $E = 120\pi h\, I/(\lambda d)$, when d is more than a wave-length.

In this case a method due to Commander Pession, of the Italian Navy, in which three aerials are used, can be successfully employed to determine the experimental effective height of each. Briefly the method may be described as follows:

Let A, B, C be any three radio stations. If A sends to B with a known transmitting current and B measures his received current, aerial resistance, wave-length and distance, then the product $h_A h_B$ can be determined from the transmission formula, for

$$h_A h_B = \frac{\lambda d R i}{120\pi I}$$

where the quantities are all known, namely, I the transmitting current, i the received current, λ the wave-length, R the resistance of the aerial, and d the distance apart of the stations.

Now the ratio of h_A to h_B may be determined at C, for the relative strength of signals at A and B respectively depends on the ratio of the effective heights h_A and h_B, the other quantities entering into the determination being observed or measured. The product and ratio of h_A and h_B both being known, the values of each, i.e. h_A and h_B, may be separately determined.

With regard to the accuracy of the Hertzian transmission formula, we have fortunately in the work of Sommerfield a very complete discussion of the field produced by a radially symmetrical transmitting aerial sending radio waves over the surface of a semi-conducting medium. A result that may be gleaned from this work is that the form of the transmission formula, i.e. $AhI/(\lambda d)$ is correct up to a distance which is large compared with the wave-length if the conductivity is sufficiently great. The determining factor is the quantity which he calls a, namely,

$$a = \frac{x_1^2}{x_2^2}\sqrt{\left(\frac{k_1^2 - k_2^2}{k_1^2}\right)}\sqrt{\left(\frac{rk_1}{2i}\right)}$$

where $k^2 = \dfrac{\epsilon\mu n^2 + i\mu\sigma n}{c^2}$

ϵ = dielectric constant,
μ = permeability,
n = frequency,
$x_1^2 = \dfrac{k_1^2}{\mu_1}$ and $x_2^2 = \dfrac{k_2^2}{\mu_2}$
σ = conductivity,
r = distance,

and the suffixes 1 and 2 refer to the air and earth respectively.

He shows that in order that the transmission from $E = AhI/(\lambda r)$ may hold, the quantity a^2 must be small compared with unity; this quantity is approximately equal to $\pi r/[\lambda(\epsilon_2 + 2\pi i\{\sigma c\lambda\})]$, and is small in all practical cases for values of r equal to many wave-lengths.

Unfortunately, Sommerfield's work is not in such a form that A and h can be determined from the physical dimensions of the transmitter, so that we cannot assume $A_0 = 120\pi$ as in the Hertzian formula. It will be observed that the error in the Pession three-aerial method is an error in scale, so to speak, occasioned by using the value 120π instead of A_0, whatever it.

may be. According to the measurements we have made, however, the difference between A_0 and 120π appears to be too small to be measurable with any accuracy.

The procedure was briefly as follows. The three-aerial method was used to determine the effective heights of aerials at Broomfield, Writtle, and the "College" (Rectory-lane, Springfield) respectively, assuming $A_0 = 120\pi$. A frame aerial was then erected at Broomfield and the E.M.F. due to a signal from the Writtle aerial was determined by means of the signal-measuring apparatus. The observed value of E.M.F. induced in the frame was then compared with the E.M.F. calculated on the basis of the 120π formula, with the value of the effective height of the transmitter, also determined on the assumption that the 120π formula was correct. The agreement was satisfactory and therefore suggests that the 120π formula is sufficiently accurate for all ordinary practical working. With this preliminary we may go on to describe these tests more in detail.

After the first instrument had been designed and calibrated by methods already described, during the early months of 1921 we turned our attention to the determination of the effective height of our receiving aerial, which was erected at Broomfield. Incidentally, this provided a check on the accuracy of the signal measurement instrument. Thus:—Suppose that in measuring the effective heights by the three-aerial method the transmitting aerial A employs such a large transmitting current that the received current in B, say, could be measured by ordinary methods, i.e. thermo-ammeter, or slide-back voltage across a known inductance, then the induced E.M.F. $V = Ri$, and the transmitting current I in the transmitter A, could be measured by methods the accuracy of which is known. If now the transmitting current in A be reduced to such a value I' that the received signal E.M.F. V' can be comfortably measured by the signal measurement instrument, then the ratio of V' to I' should be the same as the ratio of V to I if the instrument is calibrated correctly. The value of V'/I' in terms of V/I will constitute a check on the accuracy of the previous methods of calibration of M, C, etc.

Experiments were carried out during March 1921 with this double aim, and the results will be given briefly here.

The three aerials used formed a triangle one end of which was at Broomfield, another at the College (Rectory-lane, Springfield), and the third at Writtle. The distances were taken from the ordnance map and were well over a wave-length in every case. The received currents were measured in each case by the following methods:

(a) An accurately calibrated thermo-ammeter;

(b) Slide-back voltage across a known inductance; and in all cases a satisfactory agreement was obtained.

The resistance was measured by the slide-back method (the reduction in current on inserting a known resistance being noted) already described. The wave-length used was about 900 m.

The results obtained were as follows:

(1) Effective height of Broomfield aerial 10·5 m.
(2) Effective height of Writtle aerial .. 10·5 m.
(3) Effective height of College aerial .. 14·8 m.

The calculated effective height of Broomfield aerial is 16·1 m (on the assumption that the earth is perfectly conducting); and that of Writtle aerial is 15·3 m.

It will be seen that the observed values are in each case much less than the calculated values. This is no doubt largely due to the capacity of the aerial to the masts and stays; in the Broomfield aerial the central mast and stays are very close to the aerial.

The Broomfield receiving aerial was modified later, first in order to avoid the central supporting mast and its uncertain capacity to the aerial, and secondly to make it simpler, more portable, and easier to erect, so that similar aerials could easily be erected elsewhere. This was to make comparative measurements possible.

This aerial was held up by two 70 ft. steel section masts 200 ft. apart. It consisted of a single 7/19 phosphor-bronze-wire horizontal member 180 ft. long, and a single vertical wire soldered to the centre of the horizontal member, forming a T. Recent measurements (on 4 700 m wave-length) show that the effective height is practically 14 m. This is the aerial on which all the more important measurements have been made.

Radiation check on calibration.—Writtle was chosen as the transmitting station. The receiving aerial was the original five-mast one erected at Broomfield. Signals were sent out by Writtle on a 5 150 m wave-length, the transmitting current varying from 0·2 to 0·6 ampere. The following table shows the actual E.M.F. (in microvolts), the transmitting current I, and gives the actual E.M.F. observed and the calculated values.

TABLE 1.

Transmitting current, amp.	Microvolts calculated	Microvolts measured	Ratio $\frac{\text{observed}}{\text{calculated}}$
0·50	1 660	1 470	0·89
0·40	1 110	1 115	1·005
0·30	832	778	0·936
0·30	832	758	0·910
0·20	554	558	1·006

Further check.—A further check of the same set was made, using a frame receiving aerial in place of the vertical aerial at Broomfield. This aerial consisted of a rectangle, 30 ft. high by 40 ft. long, supported on two wooden masts 40 ft. high, stayed with rope stays. The frame was oriented so that the transmitting station at Writtle was in its plane.

The effective area of such an aerial can be calculated with a fair degree of precision, and when the effective height of the transmitting aerial is known it should be possible to calculate with fair accuracy the E.M.F. induced in the aerial for a given transmitting current, according to the formula

$$E = \frac{377 h_1 2A\pi}{\lambda^2 d}$$

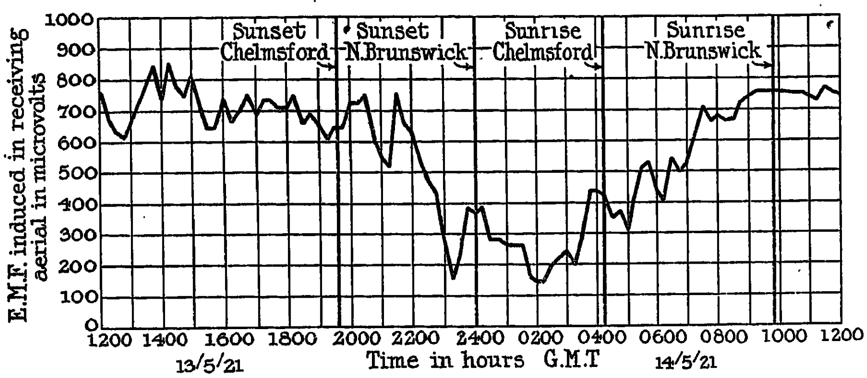


FIG. 5.—Chart showing variation in strength of received signals during 24 hours from 1200 G.M.T., 13 May, to 1200 G.M.T., 14 May, 1921. Transmitting station, New Brunswick; receiving station, Chelmsford.

Effective height of transmitting aerial = 75 m.
Effective height of receiving aerial = 14 m.
Distance = 5 420 km; wave-length = 13 600 m.
Current in transmitting aerial = 550 amperes.
Zenith angle = 48·78°.

Austin-Cohen formula: $I_2R_2 = \frac{377h_1h_2I_1}{\lambda d}\sqrt{\left(\frac{\theta}{\sin\theta}\right)}\epsilon^{-0 \cdot 0015d/\sqrt{\lambda}}$ gives E.M.F. induced in receiving aerial = 347 microvolts. Mean daylight measured value = 750 microvolts. $\frac{\text{Measured}}{\text{Austin-Cohen}} = 2 \cdot 16$.

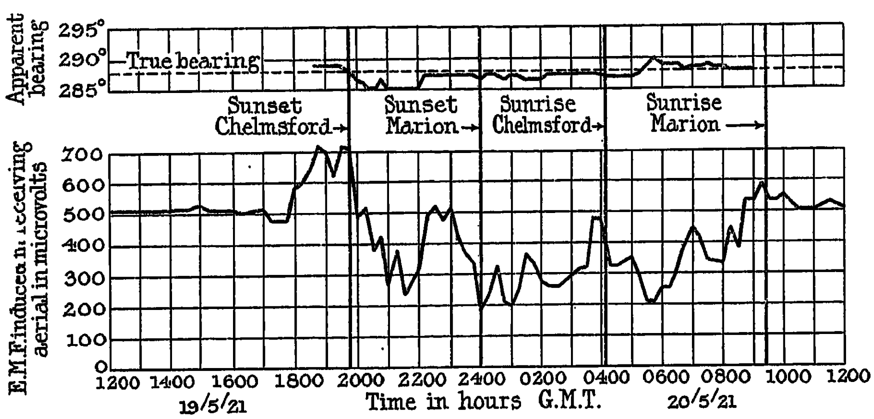


FIG. 6.—Chart showing variation in strength and divergence from true bearing of received signals during 24 hours from 1200 G.M.T., 19 May, to 1200 G.M.T., 20 May, 1921. Transmitting station, Marion; receiving station, Chelmsford.

Effective height of transmitting aerial = 75 m.
Effective height of receiving aerial = 14 m.
Distance = 5 310 km; wave-length = 11 600 m.
Current in transmitting aerial = 380 amperes.
Zenith angle = 47·71°.

Austin-Cohen formula: $I_2R_2 = \frac{377h_1h_2I_1}{\lambda d}\sqrt{\left(\frac{\theta}{\sin\theta}\right)}\epsilon^{-0 \cdot 0015d/\sqrt{\lambda}}$ gives E.M.F. induced in receiving aerial = 248 microvolts. Mean daylight measured value = 517 microvolts. $\frac{\text{Measured}}{\text{Austin-Cohen}} = 2 \cdot 08$.

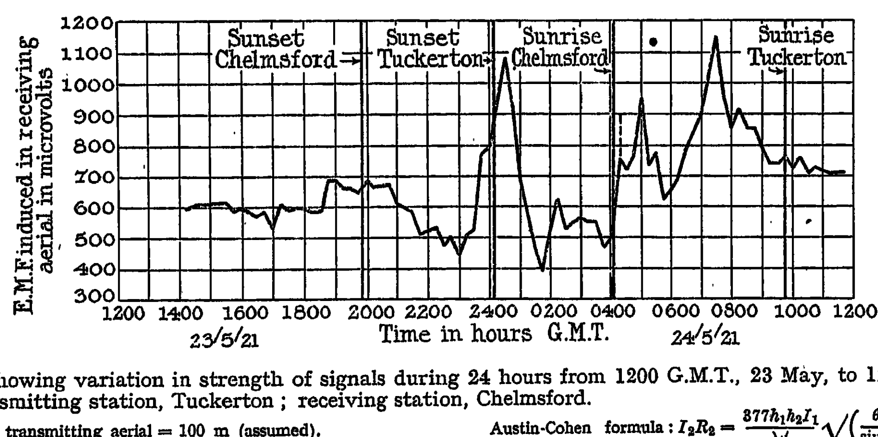


FIG. 7.—Chart showing variation in strength of signals during 24 hours from 1200 G.M.T., 23 May, to 1200 G.M.T., 24 May, 1921. Transmitting station, Tuckerton; receiving station, Chelmsford.

Effective height of transmitting aerial = 100 m (assumed).
Effective height of receiving aerial = 14 m.
Distance = 5 520 km; wave-length = 16 000 m.
Current in transmitting aerial = 400 amperes.
Zenith angle = 48·75°.

Austin-Cohen formula: $I_2R_2 = \frac{377h_1h_2I_1}{\lambda d}\sqrt{\left(\frac{\theta}{\sin\theta}\right)}\epsilon^{-0 \cdot 0015d/\sqrt{\lambda}}$ gives E.M.F. induced in receiving aerial = 319 microvolts. Mean daylight measured value = 660 microvolts. $\frac{\text{Measured}}{\text{Austin-Cohen}} = 2 \cdot 07$.

where h = effective height of transmitter,
A = area of frame,
λ = wave-length,
d = distance apart.

This test was made on an 895 m wave-length, transmitting current 2·0 amperes, effective height 10·5 m, d = 2·96 km. The calculated value of the induced E.M.F. was 2 360 microvolts; and the observed value 2 430 ± 130. But the test was extremely difficult and the whole circuit had to be balanced so as to eliminate the vertical component.

These tests show that the accuracy of calibration is sufficient for the purpose.

Original Experiments—American Stations.

The first serious attempts to measure signals with this apparatus were made early in 1921. A more or less systematic set of measurements was made on signals from the Radio Corporation transatlantic stations at Marion, New Brunswick, and Tuckerton, and latterly at Rocky Point. The period during which these measurements were made was from May to practically the end of the year. Measurements were made at Broomfield, near Chelmsford, throughout the whole period, and also comparison experiments were made at various times at Girvan on the west coast of Scotland (near Glasgow), at Towyn in North Wales, and at Poldhu in Cornwall, respectively.

The results of the original experiments made in May 1921 were given in a discussion on long-distance transmission before the Institution,* but will be included here for the sake of completeness.

Figs. 5, 6 and 7 show the result of a 24-hour test carried out as follows:—

May 13 to 14, on New Brunswick;
May 19 to 20, on Marion; and
May 23 to 24, on Tuckerton.

* *Journal I.E.E.*, 1921, vol. 59, p. 677.

Day variations are fairly small but, as usual, night variations are considerable.

The transmission data for the three stations, as well as the mean day received E.M.F. in microvolts per metre, are given in Table 2.

Figs. 8 to 13 show a series of diurnal measurements made simultaneously at Broomfield and Girvan between July 5th and 10th.

Signals are considerably greater at Girvan than at Broomfield, i.e. about 1½ times as strong. This increase is due not only to the reduction in distance (see Table 3, cols. 8 and 9) but also no doubt to land absorption across England and Ireland.

A noticeable feature is that the night variations at Girvan and Broomfield run concurrently and, while the maxima and minima do not occur exactly at the same time, the form of the curve in the two cases is very similar for any given station. There appears to be very little relation, however, between the variations of two different stations; for instance, there is a very marked minimum on New Brunswick at 0300, while the signals in Marion show a peak between 0300 and 0400. Perhaps the difference is partly due to the fact that the curves were taken on different nights, although it is reported from Towyn that the minima at 0300 and 0800 roughly are of regular occurrence on New Brunswick.

A third series of tests was made simultaneously at Broomfield and Towyn (North Wales) during the period August 31 to September 9. Night readings were, however, not taken and attention was confined to day readings, these being very much more constant and reliable. The results are given in Table 4 and show the variations which may occur from day to day.

The signals at Towyn are only slightly better than those at Broomfield, i.e. between 12 per cent and 30 per cent.

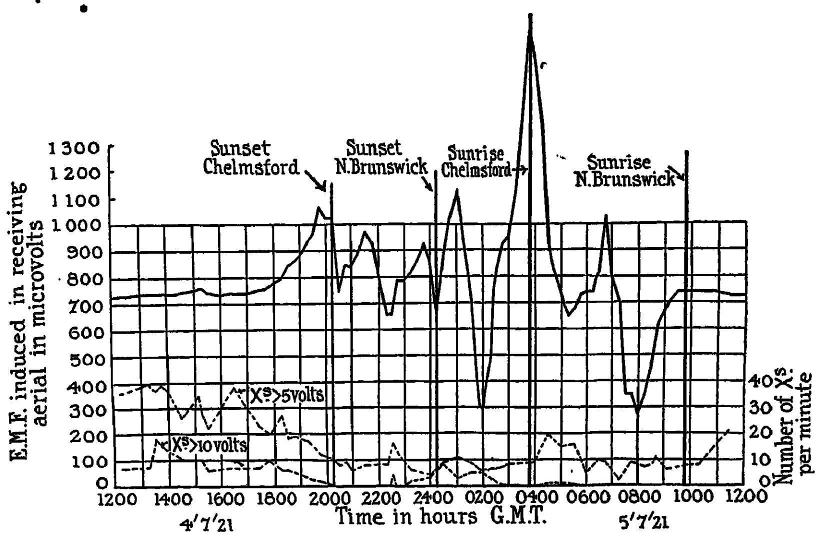
A final series of tests was carried out simultaneously at Broomfield and Poldhu (Cornwall). This acts as a check on the Girvan results, for Poldhu is as favourable a site for reception as Girvan, there being no intervening

Table 2.

Date	Station	Microvolts per metre	Wave-length	Transmission current	Height	Distance
1921		μV/m	km	amps.	m	km
May 13–14	New Brunswick	53·5	13·6	550	67	5 650
,, 19–20	Marion	37·0	11·5	380	63	5 310
,, 23–24	Tuckerton	47·1	16·0	400	90	5 700

Table 3.

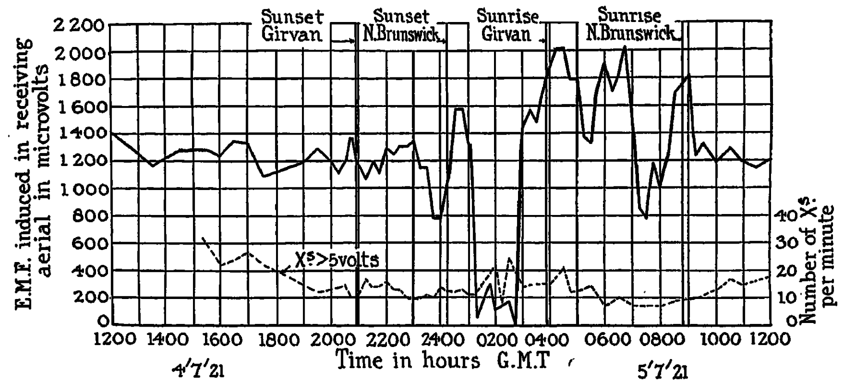
Date	Station	Broomfield	Girvan	Wave-length	Transmission current	Height	Distance from Chelmsford	Distance from Girvan
1921		μV/m	μV/m	km	amps.	m	km	km
May 4–5 ..	New Brunswick	52·8	88·6	13·6	516	67	5 650	5 190
,, 6–7 ..	Marion	40·7	47·8	11·5	530	63	5 310	4 850
,, 8–9 ..	Tuckerton	52·3	90·5	16·0	400	90	5 700	5 250



Effective height of transmitting aerial = 75 m.
Effective height of receiving aerial = 14 m.
Distance = 5 420 km; wave-length = 13 600 m.
Current in transmitting aerial = 516 amperes.
Zenith angle = 48·75°.

Austin Cohen formula:
$$I_2R_2 = \frac{377h_1h_2I_1}{\lambda d}\sqrt{\left(\frac{\theta}{\sin\theta}\right)}\epsilon^{-0\cdot0015d/\sqrt{\lambda}}$$
gives E.M.F. induced in receiving aerial = 326 microvolts. Mean daylight measured value = 740 microvolts. $\frac{\text{Measured}}{\text{Austin-Cohen}} = 2\cdot26$.

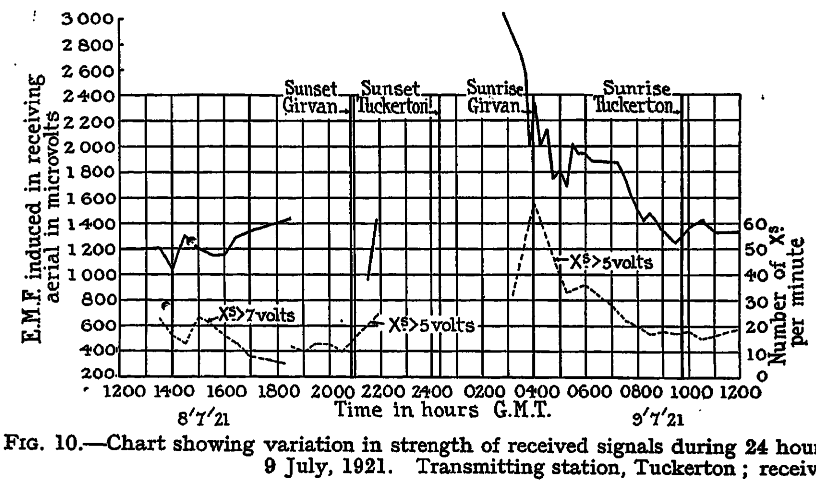
FIG. 8.—Chart showing variation in strength of received signals during 24 hours from 1200 G.M.T., 4 July, to 1200 G.M.T., 5 July, 1921. Transmitting station, New Brunswick; receiving station, Chelmsford.



Effective height of transmitting aerial = 75 m.
Effective height of receiving aerial = 14 m.
Distance = 5 180 km; wave-length = 13 600 m.
Current in transmitting aerial = 516 amperes.
Zenith angle = 46·64°.

FIG. 9.—Chart showing variation in strength of received signals during 24 hours from 1200 G.M.T., 4 July, to 1200 G.M.T., 5 July, 1921. Transmitting station, New Brunswick; receiving station, Girvan.

Austin-Cohen formula: $I_2R_2 = \frac{377h_1h_2I_1}{\lambda d}\sqrt{\left(\frac{\theta}{\sin\theta}\right)}\epsilon^{-0\cdot0015d/\sqrt{\lambda}}$ gives E.M.F. induced in receiving aerial = 371 microvolts. Mean daylight measured value = 1 240 microvolts. $\frac{\text{Measured}}{\text{Austin-Cohen}} = 3\cdot35$.



Effective height of transmitting aerial = 100 m.
Effective height of receiving aerial = 14 m.
Distance = 5 255 km; wave-length = 16 000 km.
Current in transmitting aerial = 400 amperes.
Zenith angle = 47·46°.

FIG. 10.—Chart showing variation in strength of received signals during 24 hours from 1200 G.M.T., 8 July, to 1200 G.M.T., 9 July, 1921. Transmitting station, Tuckerton; receiving station, Girvan.

Austin-Cohen formula: $I_2R_2 = \frac{377h_1h_2I_1}{\lambda d}\sqrt{\left(\frac{\theta}{\sin\theta}\right)}\epsilon^{-0\cdot0015d/\sqrt{\lambda}}$ gives E.M.F. induced in receiving aerial = 370 microvolts. Mean daylight measured value = 264 microvolts. $\frac{\text{Measured}}{\text{Austin-Cohen}} = 3\cdot43$.

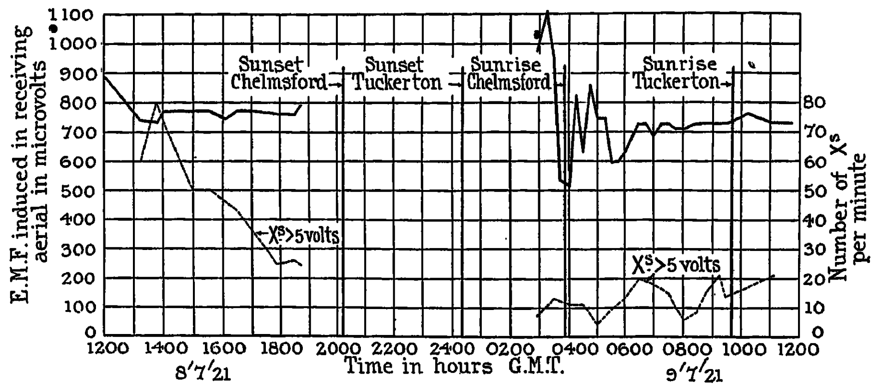


FIG. 11.—Chart showing variation in strength of received signals during 24 hours from 1200 G.M.T., 8 July, to 1200 G.M.T., 9 July, 1921. Transmitting station, Tuckerton; receiving station, Chelmsford.

Effective height of transmitting aerial = 100 m.
Effective height of receiving aerial = 14 m.
Distance = 5 520 km; wave-length = 16 000 m.
Current in transmitting aerial = 400 amperes.
Zenith angle = 49·75°.

Austin-Cohen formula: $I_2R_2 = \frac{377h_1h_2I_1}{\lambda d}\sqrt{\left(\frac{\theta}{\sin\theta}\right)}\epsilon^{-0\cdot0015d/\sqrt{\lambda}}$ gives E.M.F. induced in receiving aerial = 310 microvolts. Mean daylight measured value = 750 microvolts. $\frac{\text{Measured}}{\text{Austin-Cohen}} = 2\cdot35.$

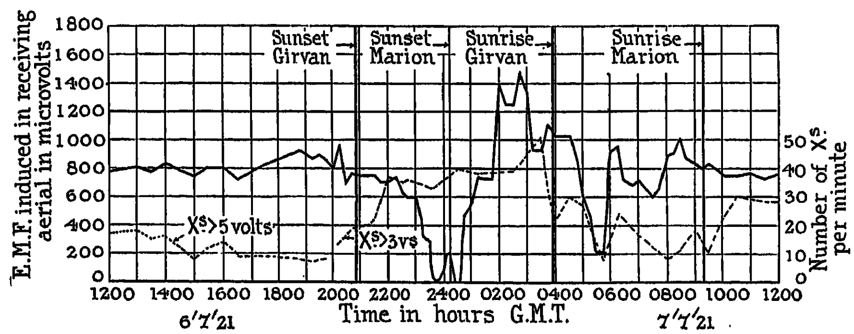


FIG. 12.—Chart showing variation in strength of received signals during 24 hours from 1200 G.M.T., 6 July, to 1200 G.M.T., 7 July, 1921. Transmitting station, Marion; receiving station, Girvan.

Effective height of transmitting aerial = 75 m.
Effective height of receiving aerial = 16 m.
Distance = 4 870 km; wave-length = 11 500 m.
Current in transmitting aerial = 580 amperes.
Zenith angle = 43·87°.

Austin-Cohen formula: $I_2R_2 = \frac{377h_1h_2I_1}{\lambda d}\sqrt{\left(\frac{\theta}{\sin\theta}\right)}\epsilon^{-0\cdot0015d/\sqrt{\lambda}}$ gives E.M.F. induced in receiving aerial = 455 microvolts. Mean daylight measured value = 806 microvolts. $\frac{\text{Measured}}{\text{Austin-Cohen}} = 1\cdot77.$

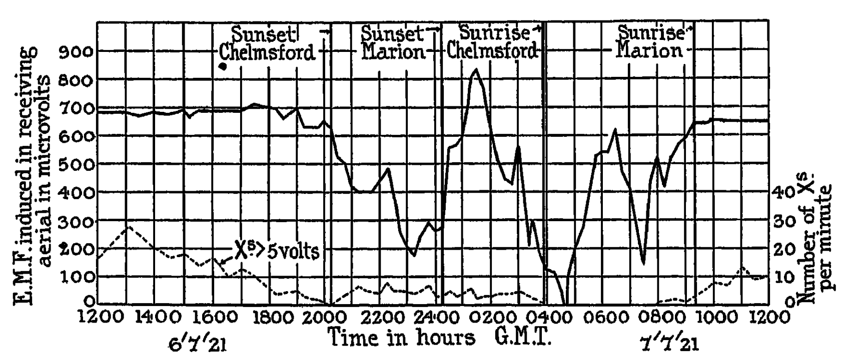


FIG. 13.—Chart showing variation in strength of received signals during 24 hours from 1200 G.M.T., 6 July, to 1200 G.M.T., 7 July, 1921. Transmitting station, Marion; receiving station, Chelmsford.

Effective height of transmitting aerial = 75 m.
Effective height of receiving aerial = 14 m.
Distance = 5 310 km; wave-length = 11 500 m.
Current in transmitting aerial = 580 amperes.
Zenith angle = 47·71°.

Austin-Cohen formula: $I_2R_2 = \frac{377h_1h_2I_1}{\lambda d}\sqrt{\left(\frac{\theta}{\sin\theta}\right)}\epsilon^{-0\cdot0015d/\sqrt{\lambda}}$ gives E.M.F. induced in receiving aerial = 346 microvolts. Mean daylight measured value = 670 microvolts. $\frac{\text{Measured}}{\text{Austin-Cohen}} = 1\cdot94.$

land in either case. These tests were carried out during the period October 11–19, 1921.

The results for the stations WQK (Rocky Point on Long Island) and Glace Bay (GB) (valve set) are included here. WQK had started a service a short while previously, and GB had also been changed from spark to continuous wave and was therefore available for measurements.

The mean daily values of the E.M.F. at Poldhu and Broomfield are given in Table 5.

These results agree roughly with those obtained at Girvan, except in the case of Marion, the signals from which are considerably stronger at Poldhu.

TABLE 4.

Marion.

Date	At Towyn	At Broomfield
1921	μV/m	μV/m
Aug. 31	43·8	42·0
Sept. 1	39·3	40·5
,, 2	46·8	42·9
,, 3	50·2	37·0
,, 5	46·0	36·1
,, 6	48·6	38·3
,, 7	47·7	40·8
,, 8	44·4	39·4
,, 9	44·2	37·9
Mean	42·32	35·49

New Brunswick.

Date	At Towyn	At Broomfield
1921	μV/m	μV/m
Aug. 31	64·7	59·3
Sept. 1	62·0	54·0
,, 2	83·0	76·2
,, 3	82·6	79·0
,, 6	72·8	57·3
,, 7	70·5	75·2
,, 8	76·0	59·6
,, 9	72·2	66·7
Mean	73·0	66·0

Tuckerton.

Date	At Towyn	At Broomfield
1921	μV/m	μV/m
Aug. 31	67·4	59·6
Sept. 1	67·8	65·6
,, 2	76·5	58·8
,, 3	71·4	50·0
,, 5	66·9	52·9
,, 6	64·1	
,, 7	67·6	44·3
,, 8	62·0	46·3
,, 9	67·3	48·6
Mean	68·0	54·0

TABLE 5.

Glace Bay.

Date	At Poldhu	At Broomfield
1921	μV/m	μV/m
Oct. 12	30·0	9·8
,, 14	30·0	7·86
,, 15	26·3	7·60
,, 17	28·1	7·43
,, 18	27·1	6·51
,, 19	27·7	7·20
Mean	27·8	7·34

Marion.

Date	At Poldhu	At Broomfield
1921	μV/m	μV/m
Oct. 11	91·5	51·9
,, 12	84·6	50·7 to 52·9
,, 13	81·4	52·7 to 55·2
,, 14	80·8	51·1
,, 15	90·7	51·2
,, 17	82·2	56·4
,, 18	74·3	45·6
,, 19	76·0	50·5
Mean	82·8	51·4

New Brunswick.

Date	At Poldhu	At Broomfield
1921	μV/m	μV/m
Oct. 11	89·5	75·0
,, 13	97·6	77·6
,, 14	83·5	63·2
,, 15	87·8	72·2
,, 17	91·4	84·3
,, 18	81·0	57·0
,, 19	82·2	64·5
Mean	87·6	70·5

Tuckerton.

Date	At Poldhu	At Broomfield
1921	μV/m	μV/m
Oct. 11	101	61·1
,, 12	95·5	59 to 61·1
,, 13	106	49·3
,, 14	105·3	59·1
,, 15	108·2	50·5
,, 17	107·3	59·7
,, 18	92·4	50·2
,, 19	102·4	64·2
Mean	102·4	56·7

Rocky Point.

Date	At Poldhu	At Broomfield
1921	μV/m	μV/m
Oct. 11	126·7	94·5
,, 12	142·1	106·4
,, 13	139·0	102·0
,, 14	134·1	103·8
,, 15	146·6	107·3
,, 17	140·0	107·5
,, 18	122·3	93·3
,, 19	133·3	108·2
Mean	135·6	102·9

This completes the systematic tests, but a series of sporadic measurements were made at Broomfield during November and December. These show a sudden and

very marked decrease in signal strength on all the American stations during the early weeks of November, and this persisted throughout the winter months. Day-

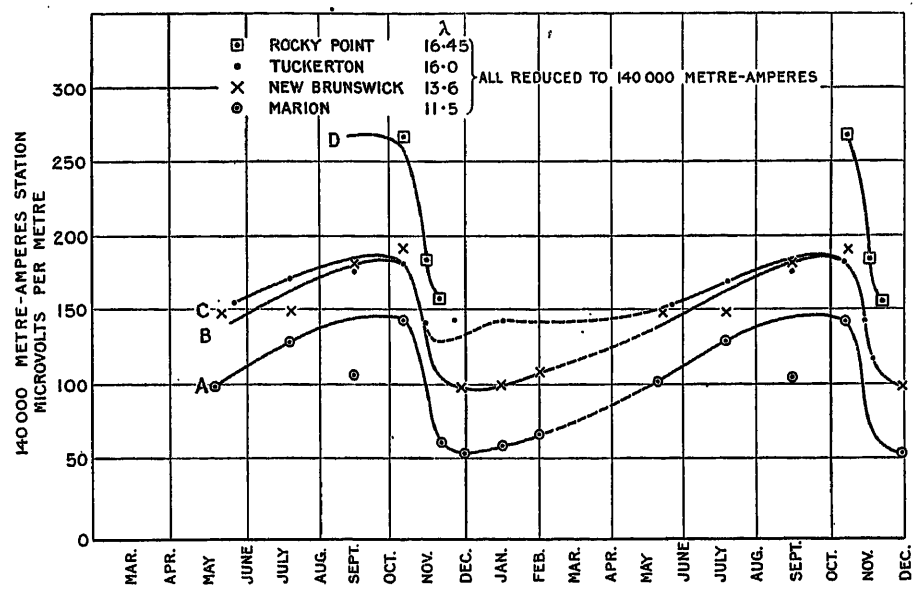


FIG. 14.—Annual variation at Chelmsford.

TABLE 6.

Analysis of Signal Strengths in Microvolts per Metre for South Africa (Kalabas Kraal, Near Cape Town).

Time	LY Bordeaux	WQL Long Island, U.S.A.	WCI Tuckerton A	WGG Tuckerton B	WQK Long Island, U.S.A.	UFT St. Assise	MUU Carnarvon	WII New Brunswick	WSO Marion (Max.)	OUI Hanover
0000		43·5	44·0	37·4	61·7	93·1		20·3		
0100		51·8	39·3	15·0	62·1	36·0		26·3		
0200		40·0	42·3	10·7	59·4					24·2
0300	25·3	41·2	40·3	20·7	60·8	26·7		25·0		10·2
0400	30·0	42·2			36·3			18·3		
0500		42·0		28·5	41·5	38·3		34·8		
0600	49·4	68·4		40·2	37·6	22·4	28·4	16·1		
0700		50·1	24·4		19·3	10·7		10·8		
0800		31·2	26·4	16·3	26·6	16·0		11·6		9·5
0900	29·8	15·9	16·4	14·6	27·7		4·64	9·65	10·0	8·9
1000	20·9	23·9		21·8	26·4	30·0	4·07	9·3	11·4	9·6
1100	23·1	21·4	15·7	15·2	23·2		8·7	15·5	5·0	9·6
1200	18·8	18·5	20·2	17·4	26·6	28·4	6·75	13·4	10·7	
1300	22·7	30·0		20·8	39·6	27·7			9·6	
1400	17·3	28·7	21·8		41·1	31·1		19·0		
1500		29·6		17·9	42·4	33·7				
1600	22·5	23·7	23·5		45·1	28·4		17·5		
1700				22·2	33·5	27·4		13·5		
1800		25·2			30·0	15·7				
1900		17·7	16·0	5·7?	18·3	23·8		10·1		
2000		19·2	12·2	12·9	25·4	42·0	7·96	7·6		20·3
2100	27·1	18·0		14·2	29·5	44·5	6·55	7·8		
2200	29·0	29·7		16·6	28·9	33·3	9·8	10·2		
2300		42·3	22·3	16·6	28·9	36·0		13·2		

light variations were also much more marked during the winter than in the summer. The average measurements are included in Fig. 14, which shows the seasonal variation in signal strength from the American stations as measured at Chelmsford. The ordinates, i.e. the signal strength in microvolts per metre, do not represent the actual signal strength received, the values being corrected to bring them all to the same metre-amperes, i.e. 140 000, so that the presentation of the

results is not complicated by individual peculiarities of the stations.

South African Signal Measurements.

Measurements of the signal strength of various stations were also made in South Africa, by Mr. L. D. Hill, with this apparatus during the summer of 1922. The actual period was Aug. 25 to Sept. 12, and therefore represents late summer conditions in Europe and America, and winter or early spring conditions in South Africa.

The results were obtained with measuring and receiving gear almost identical with that used at Broomfield and on the Australian Expedition, the standard aerial of 14 m effective height being used in conjunction with this. This aerial was generally combined with a frame aerial to give a unidirectional or "heart-shaped" diagram, the signals in this case being exactly twice as strong as with the vertical aerial alone when adjusted for maximum reception.

The results are given in Table 6 and Figs. 15 and 16, and show the diurnal variations of WQK and UFT. The latter shows a marked minimum in the half-light half-dark period, which it should be noted only lasts for a brief interval since the stations are on nearly the same longitude. This minimum is not so marked on the American stations and is perhaps due to the fact that the half-light half-dark period was of considerably greater length.

The numerical values of the oversea and overland attentuations derived from this material are discussed in greater detail later, but we anticipate these results so far as to point out that the intensity of signals from European stations, for which the route is all overland,

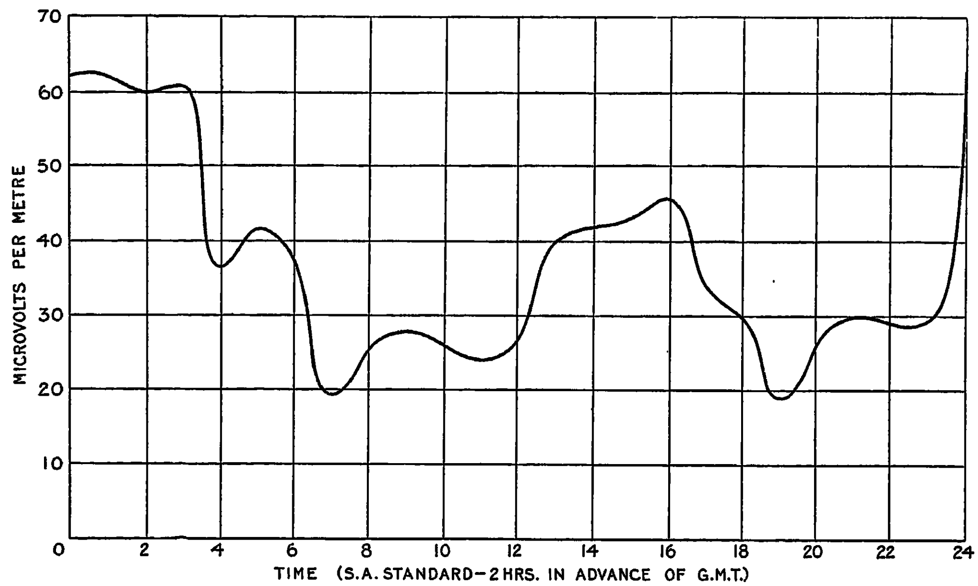


FIG. 15.—Average signal strength of WQK at Kalabas Kraal (South Africa), August–October, 1922.

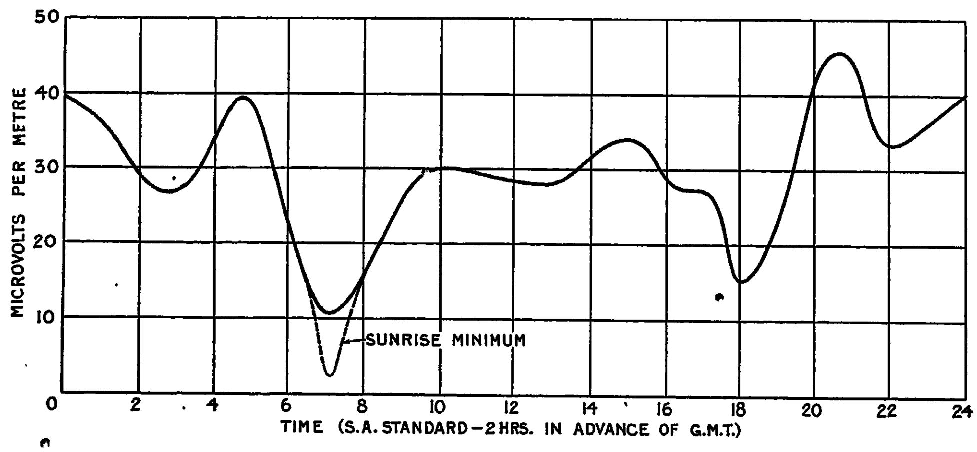


FIG. 16.—Average signal strength of UFT at Kalabas Kraal (South Africa), August–October, 1922.

is approximately halved by the presence of this land, judging by the comparative strength of the American stations for which the path is all oversea.

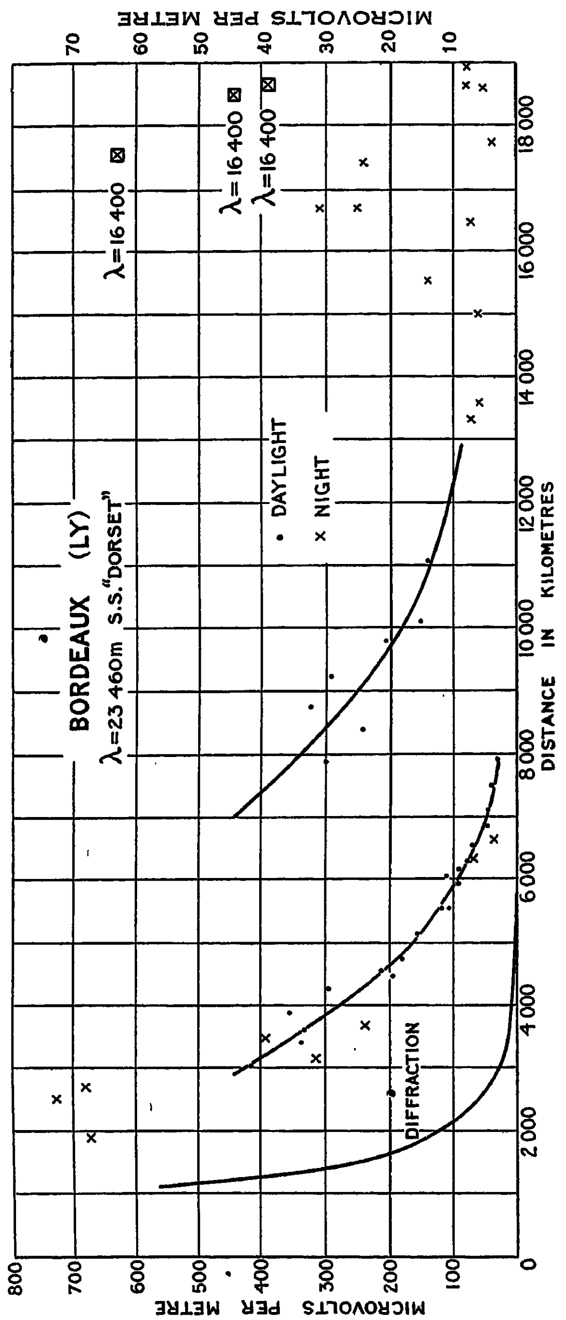


FIG. 17.

LIVERPOOL TO AUCKLAND VIA PANAMA ON S.S. "DORSET."

The following is a discussion of the results obtained on the outward voyage of the S.S. "Dorset" from Liverpool to Auckland via Panama.

Figs. 17 to 30 inclusive show the observed values of microvolts per metre of effective height for various stations, plotted against the distance in kilometres from these stations at the times the readings were taken. The values obtained when both the S.S. "Dorset" and the station under observation were in daylight are shown as dots, and the night readings and readings taken when mixed light and dark conditions intervened are shown as crosses. Although some readings at distances greater than 13 000 km are shown as "all daylight" readings, it is probable that although daylight extended to the North-East from the "Dorset" to the transmitting stations at these times, part or the whole of the signal received was from the South-West, in which direction the great-circle path followed by the signal was chiefly in darkness. The curves are therefore shown dotted at distances greater than 13 000 km. The first indication of any such reversal of signals was noticed on the 18th March, 1922, when in the Pacific Ocean at a distance of about 12 000 km from New York. The signals from the New York stations at certain times of the day, and especially when daylight extended between the S.S. "Dorset" and New York to the North-East, became blurred and often quite unreadable for several hours on the vertical aerial or a plain frame aerial, whereas they were quite readable on the heart-shape or uni-directional receiver. On the latter it was found that the signals at these times were actually received from both directions simultaneously, i.e. from the North-East and also by the long great-circle route of about 28 000 km from the South-West. The signals at these times on the vertical aerial had a sound similar to that given by two continuous-wave signals of slightly varying frequency interfering with one another. Observations taken at these times on some of the curves have been marked as variable due to "beats." This reversal of signals was also noticed on the signals from the European stations, and a similar effect was noticed at about the same time in Rio de Janeiro by the party carrying out experiments at that place. In this case Cavite in the Philippine Islands was the station on which the effect was observed. Where the S.S. "Dorset" approached and then receded from a given station, the observations are distinguished by a circle round the points on the curve. In some cases the diffraction curves have been added for comparison with the observed readings.

In Fig. 27 the majority of the stations measured are shown on the same scale, and relative signals may be seen at a glance.

In Fig. 28, for Honolulu, the arrows through the points denote the direction from which signals were received at the times the observations were taken, taking the top of the chart as North, and it will be seen that the signals received from the West are of greater values than signals at similar distances received from the North. This East and West effect is described more fully in another part of the paper.

Melbourne.—After noting the reversal of signals, as described above, on the S.S. "Dorset" in the Pacific, it was expected that the same would take place at Melbourne, and this was found to be the case. Except in the case of Bordeaux all the European stations reached two maxima or peak values as shown in the curves, one between sunrise at the European station and sunset at Melbourne when signals were from the South-East,

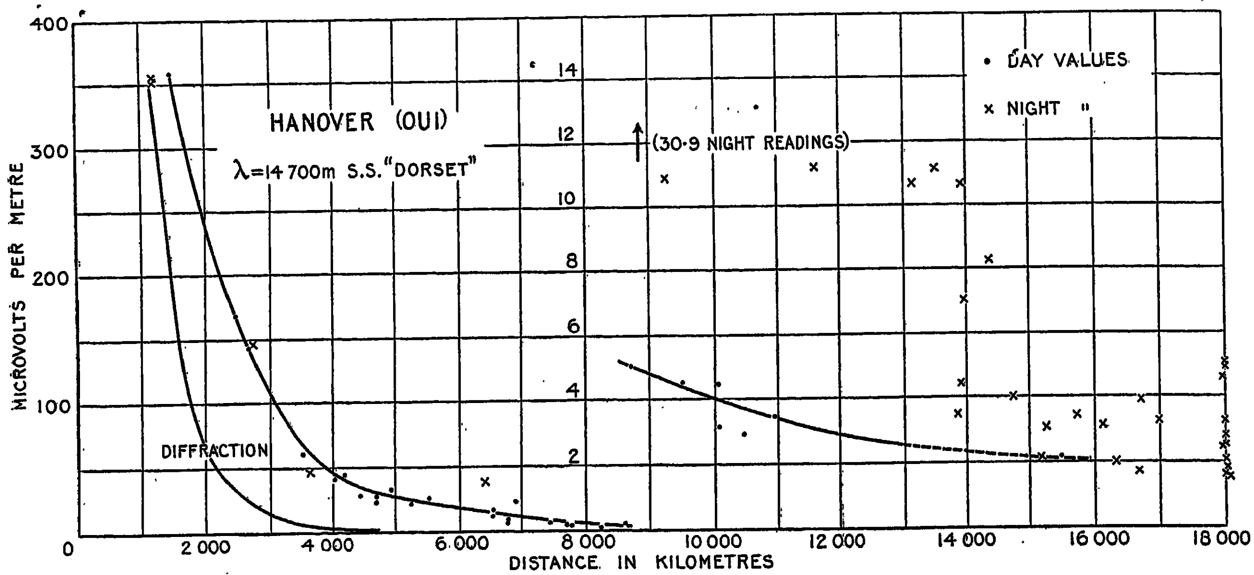


FIG. 18.

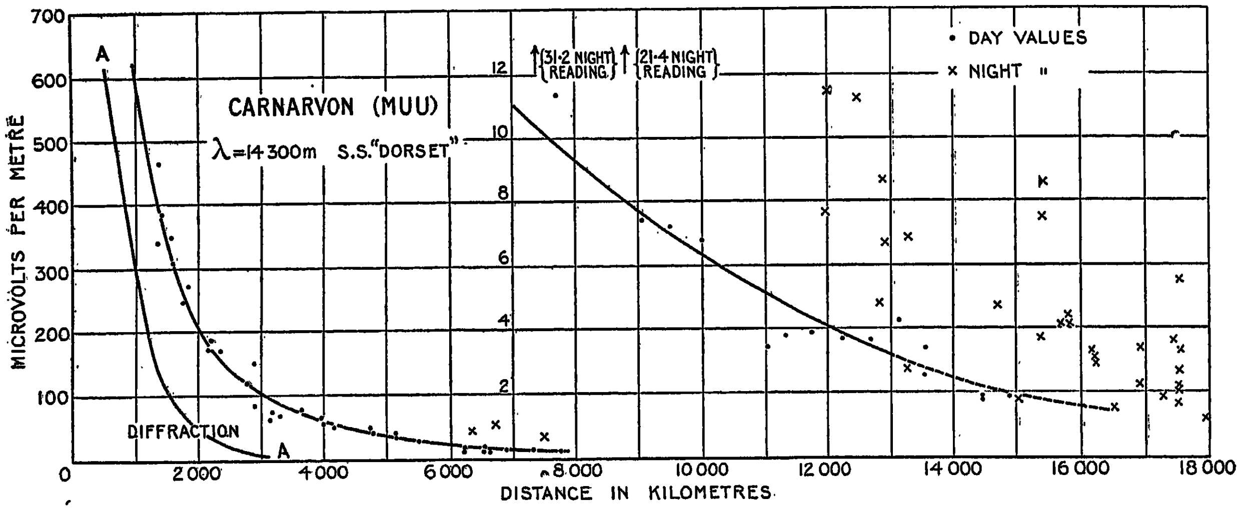


FIG. 19.

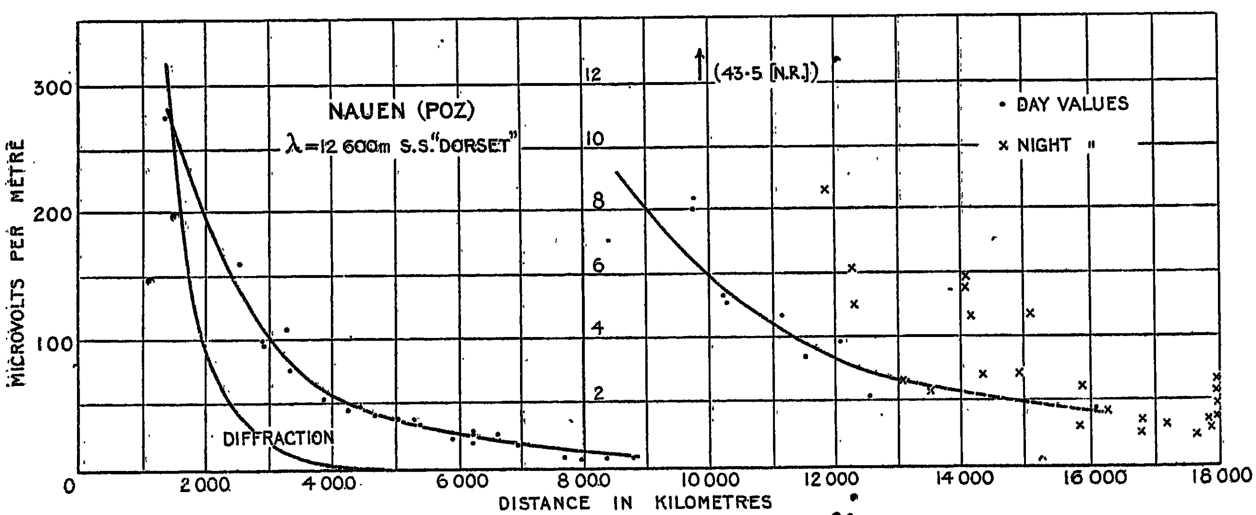


FIG. 20.

NOTE: N.R. = Night reading.

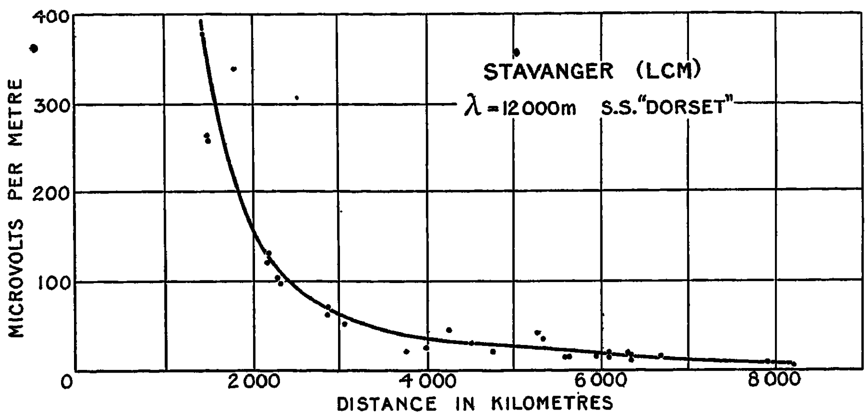


FIG. 21.

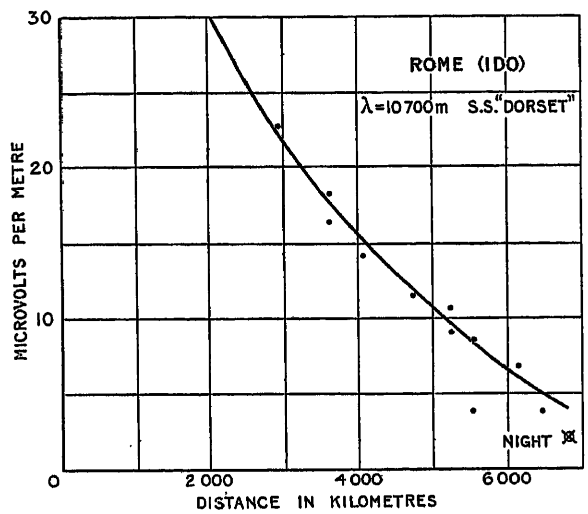


FIG. 22.

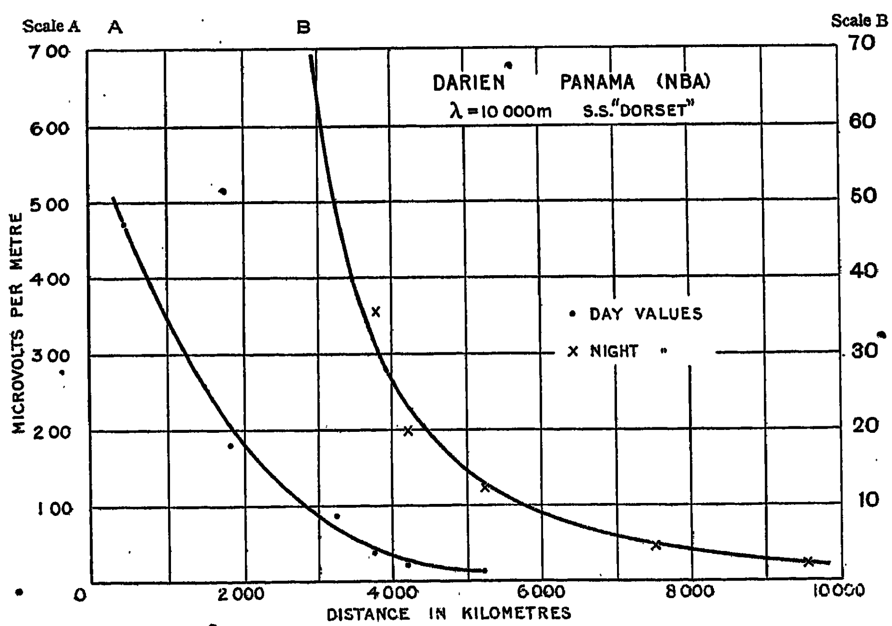


FIG. 22A.

via the Pacific, which route was mostly in darkness at that time, and the other peak between sunset at the European station and sunrise at Melbourne, when the shorter great-circle route via the Indian Ocean to the hood of Melbourne. The majority of these curves give the average of observations extending over a period of four months from the autumn to the spring in Australia, and as the times at which the "peaks" occur

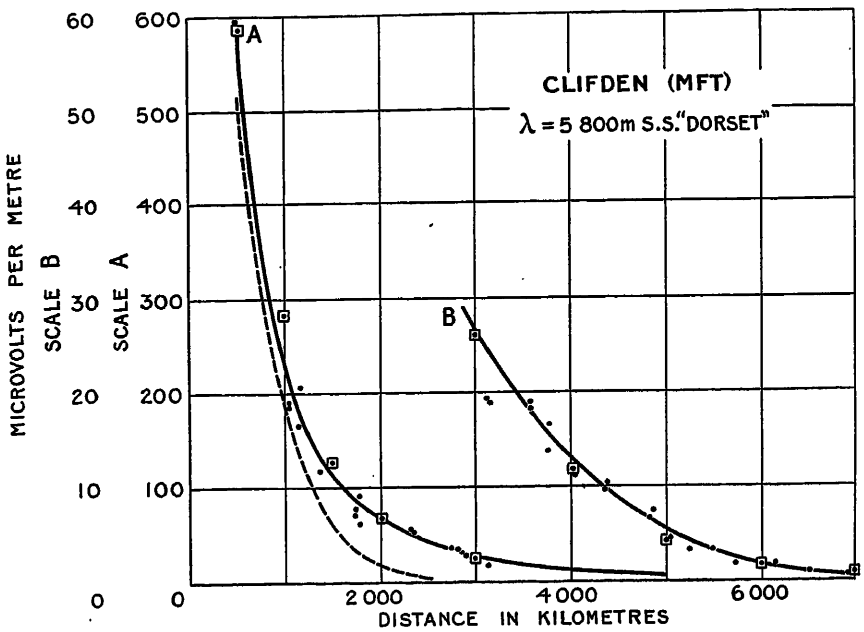


FIG. 23.

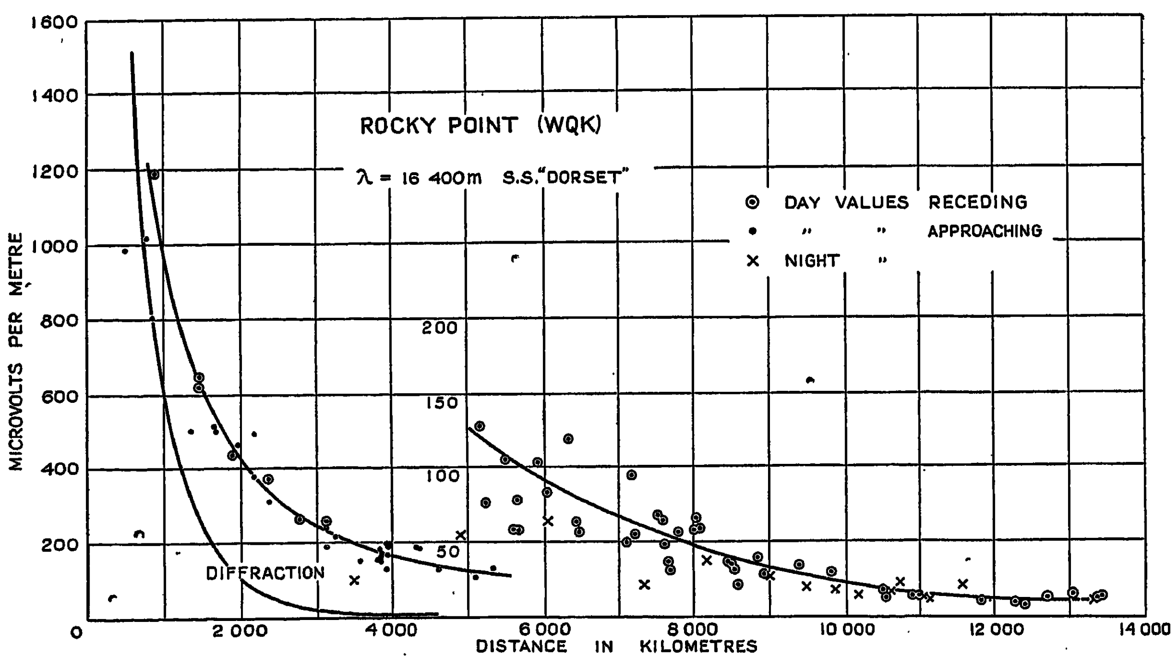


FIG. 24.

North-West was in darkness. The same reversal took place on the signals from New York.

Figs. 31 to 49 inclusive show the average curves for diurnal variation of signal strength in microvolts per metre for various stations observed in the neighbour- vary with the seasons, the peak values appear more variable and extend over rather a longer period than they would if taken over a period of only a few days, although considerable variations in the peak strengths do occur from day to day. The manner in which the

peaks vary with the seasons is shown in Figs. 38 and 44, whilst Fig. 37 shows the variation in the signal strength of Carnarvon for one day.

between 0400 and 0700 G.M.T. appeared to be rather lower than the winter values.

In Fig. 31 it will be seen that signals from Bordeaux

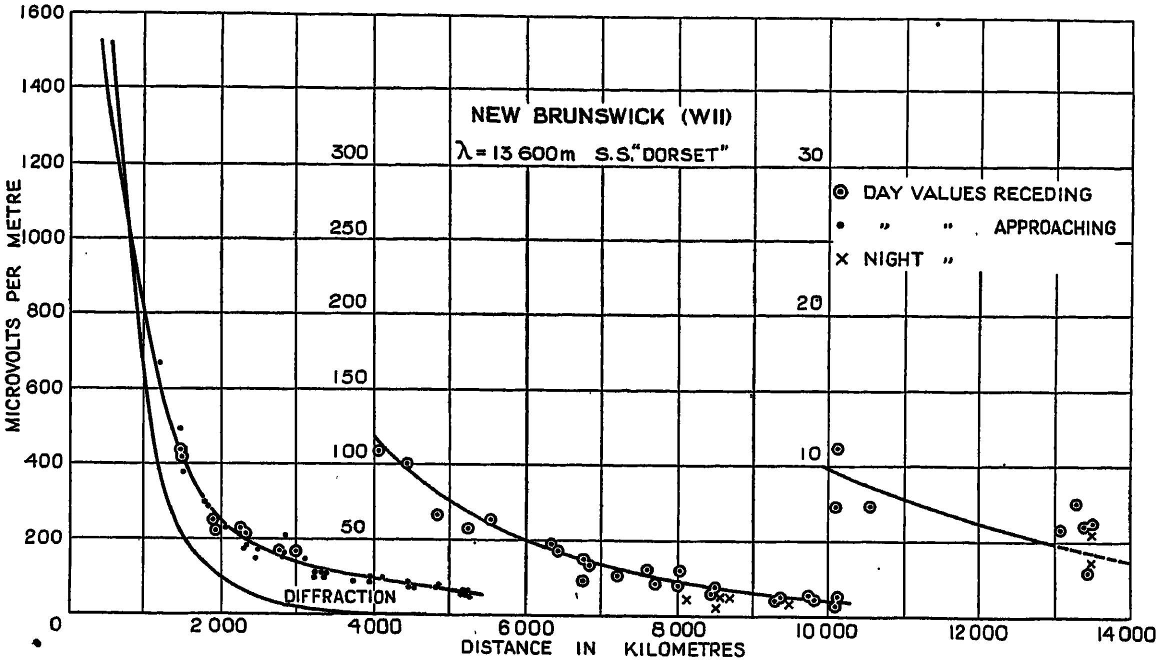


FIG. 25.

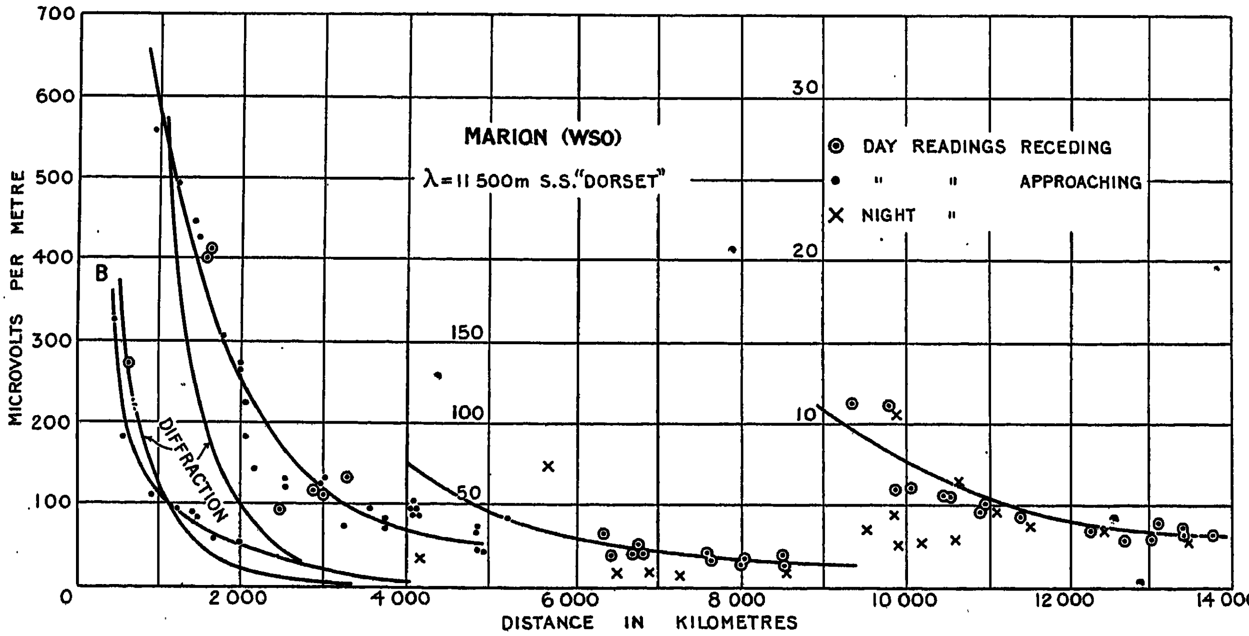


FIG. 26.

NOTE: For "B" curves, multiply the scale reading by 10.

Figs. 32 and 43 give examples of summer conditions and it will be seen that the signal strengths are very similar to the average winter values, though on some occasions the peak values of some European stations

on 23 400 m have no maximum between 0400 and 0800 G.M.T. as in the case of the other European stations, and signals on the unidirectional receiver were at this time always stronger from the North-West, whereas

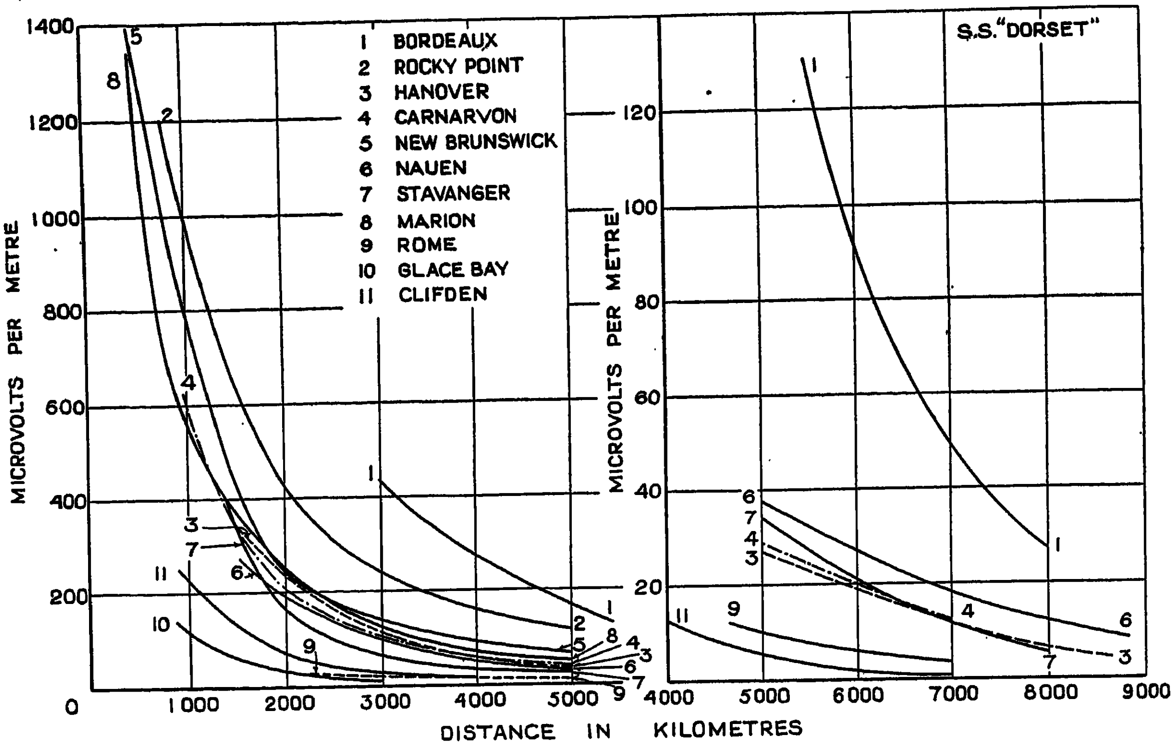


FIG. 27.

signals from the other European stations were always either equal at these times or stronger from the South-

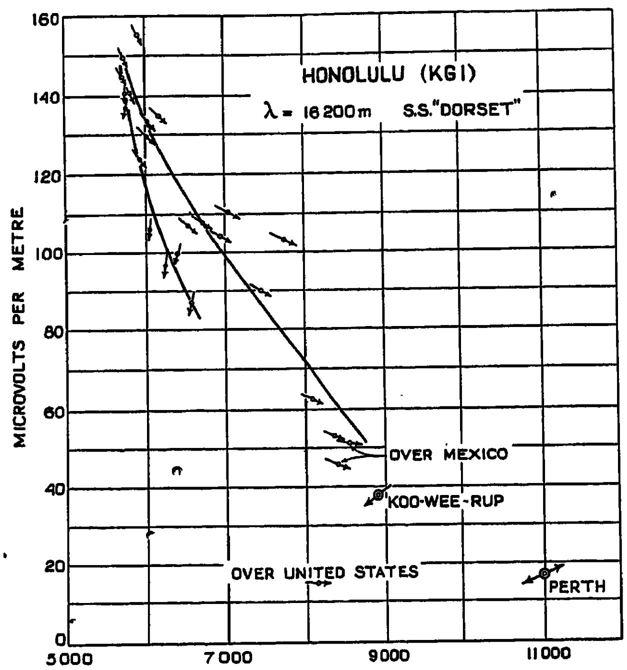


FIG. 28.

East, and, in the case of Carnarvon, Nauen and Hanover, were entirely from the South-East for three or four hours. That this difference in behaviour of signals from Bordeaux is due to the long wave-length of this station compared with the other European stations appears to be borne out by the following observations on the New York stations. Figs. 40, 42, 45, 46 and 47 show that while Coram Hill (WQL) having the longest wave-length of the New York stations reaches very much higher values of signal strength from the South-West than from the North-East, and Rocky Point and Tuckerton are also stronger or about equal in the case of the latter, the New York stations of shorter wave-length, New Brunswick and Marion, are always strongest from the North-East. The times at which the signals from New York change over also vary with the wave-length, the stations of longer wave-length always remaining from the South-Westerly direction after the shorter-wave stations have changed to the North-East, and changing back again to the South-Westerly route before the shorter waves. Owing to the above, in Melbourne at certain times two stations, both in New York, are received one from the North-East and the other from the South-West. At these change-over times New Brunswick was always more variable and appeared to hesitate about changing from one direction to the other for a longer period than the other stations, and this often had the effect of making the signals more readable than the other New York stations at these times, owing to the gain which a bi-directional signal had over a unidirectional signal when the unidirectional signal was from a similar direction to that of the atmospherics at the time.

At times when the signals from the New York and European stations were bi-directional, the beats as

escribed above were observed, and these were especially marked in the case of UFT (Paris), signals from his station being often quite unreadable, due to this ffect, for several hours a day on a vertical aerial or daylight signals, and were very variable in strength. The maximum signals received were always at sunrise at Honolulu. Signals from this station were always from the North-East only, as were signals from KET (San

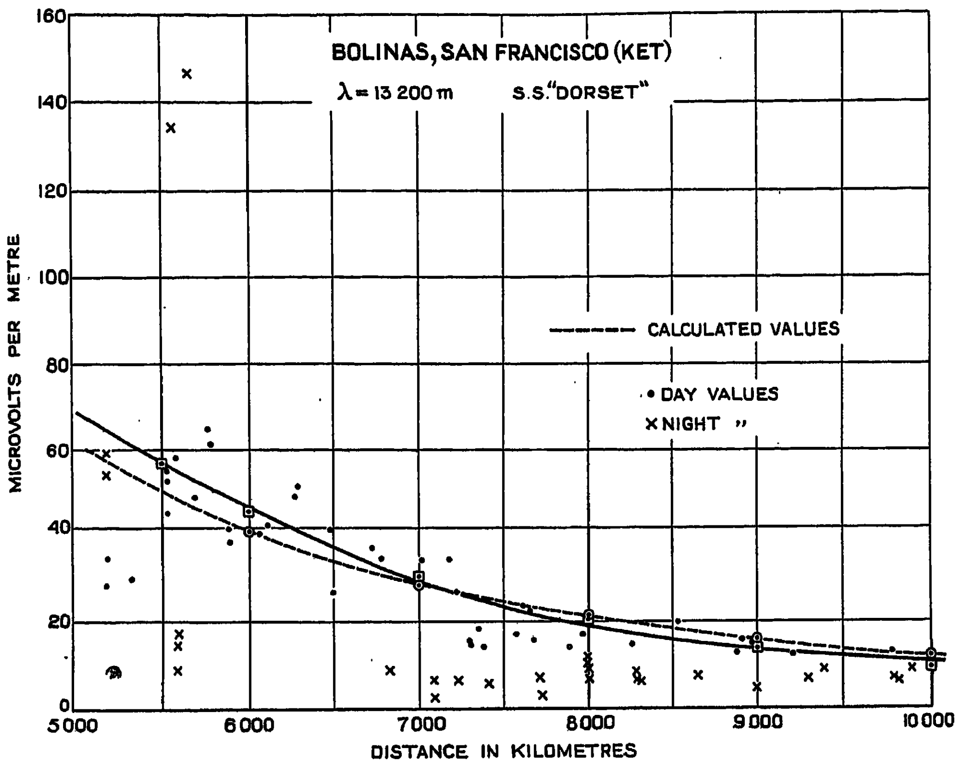


FIG. 29.

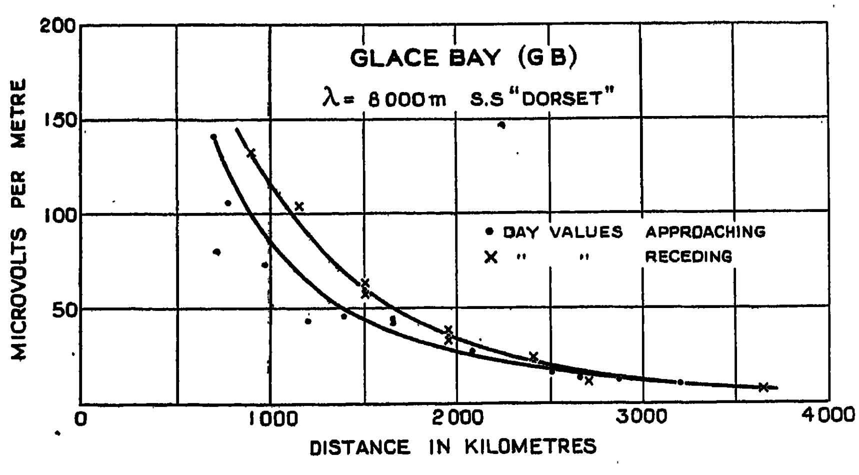


FIG. 30.

frame aerial, but always readable on the heart-shape or unidirectional receiver. These beats were also observed on signals from Honolulu at Perth (Western Australia) and various places in the Indian Ocean on the homeward voyage.

As shown in Fig. 48, signals from Honolulu during the all-dark period never reached the average of the all-Francisco) (see Fig. 49), the curves for these two stations being very similar in form.

Rocky Point and Honolulu being in much the same direction to the North-East of Melbourne, and the wave-lengths of these stations being very similar, it was not always easy to distinguish one station from the other between about 0800 and 1200 G.M.T. when both signals

were received from the North-East, but from about 2000 to 0200 G.M.T., owing to the reversal of the signals from Rocky Point and to the fact that the signals from Honolulu did not reverse, Rocky Point was received on one side of the heart-shape receiver with no trace of Honolulu, while Honolulu was received on the other side with no trace of Rocky Point.

taken at Perth (Western Australia) over a period of about five weeks during the summer. The aerials used at Melbourne and Perth were identical. Comparing these curves with those taken at Melbourne, it will be seen that Bordeaux (Fig. 50) was only heard from the North-West, and in the case of the other European stations (Figs. 51 to 54) signals were always stronger from the North-West,

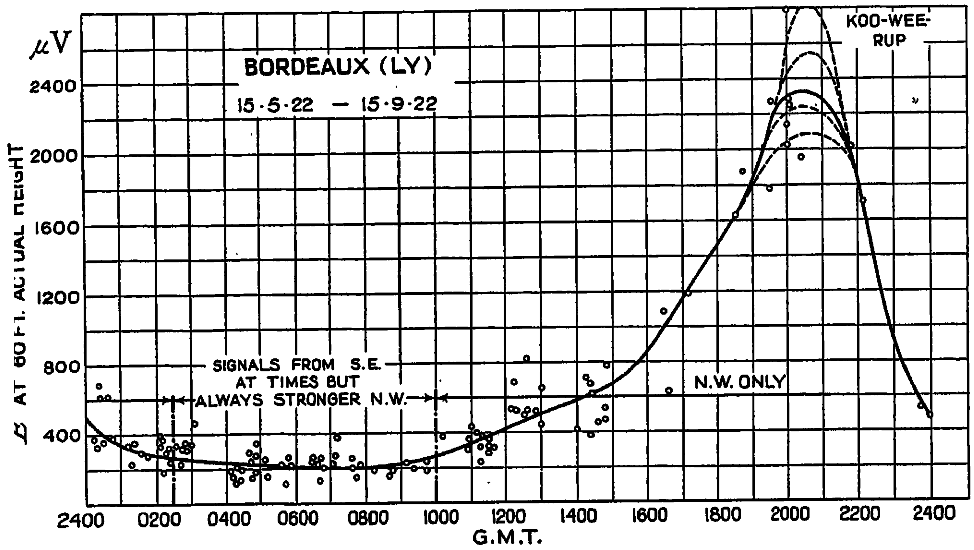


Fig. 31.

Note: Effective height = 12 metres.

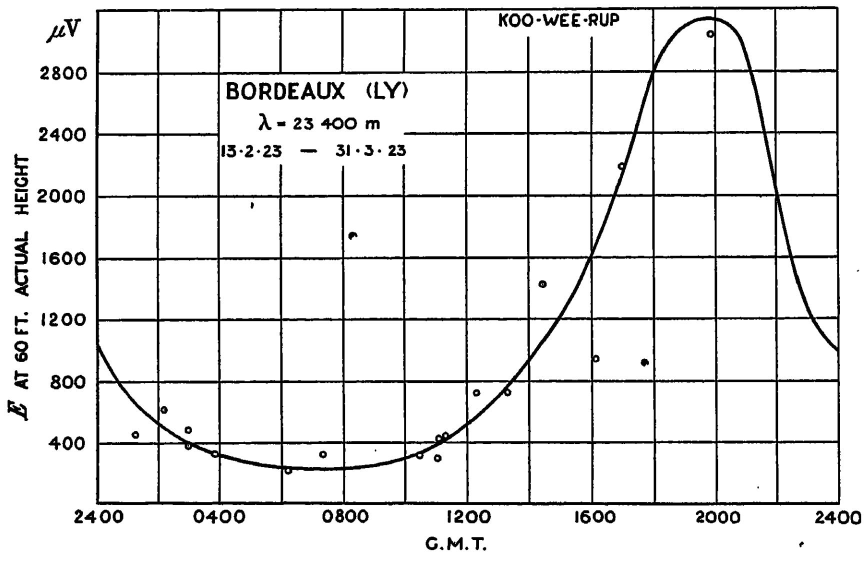


Fig. 32.

Note: Effective height = 12 metres.

Fig. 41 gives an idea of the relative signal strengths of WQL (Coram Hill) on either side of the heart-shape receiver, i.e. from the North-East and from the South-West at and near one of the two change-over periods. The strengths of signals on the vertical aerial are given at the same time as those obtained on the heart shape.

Perth.—Figs. 50 to 59 inclusive show average curves but were audible from about 0600 to 1000 G.M.T. from the South-East also. At these times "beats" were sometimes observed. It should be explained that a bi-directional signal is not always accompanied by "beats"; and the extent to which these "beats" occur, and the consequent mutilation of the signals, varies from minute to minute. Also the worst

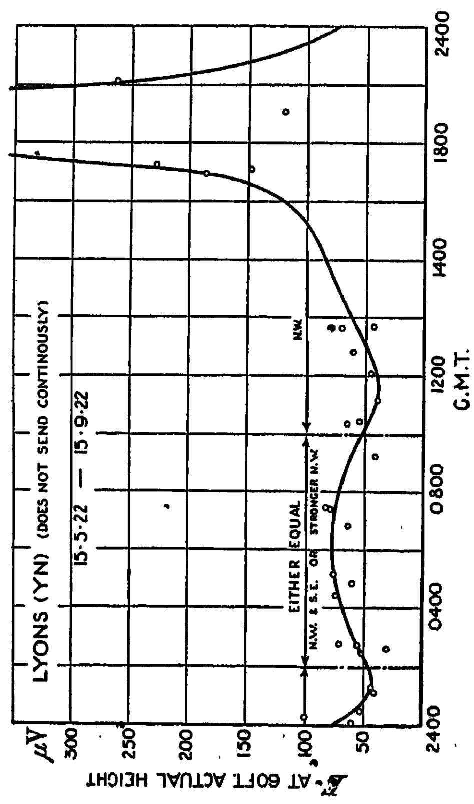


FIG. 33.—At Koo-Wee-Rup.
NOTE: Effective height = 12 metres.

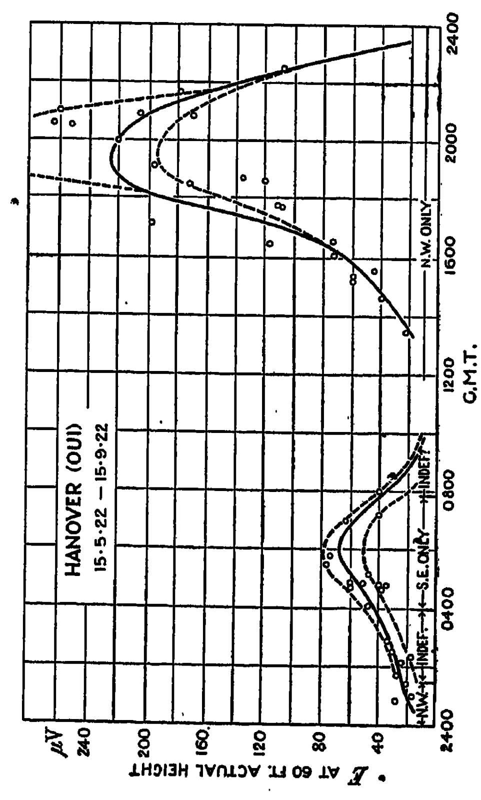


FIG. 34.—At Koo-Wee-Rup.
NOTE: Effective height = 12 metres.

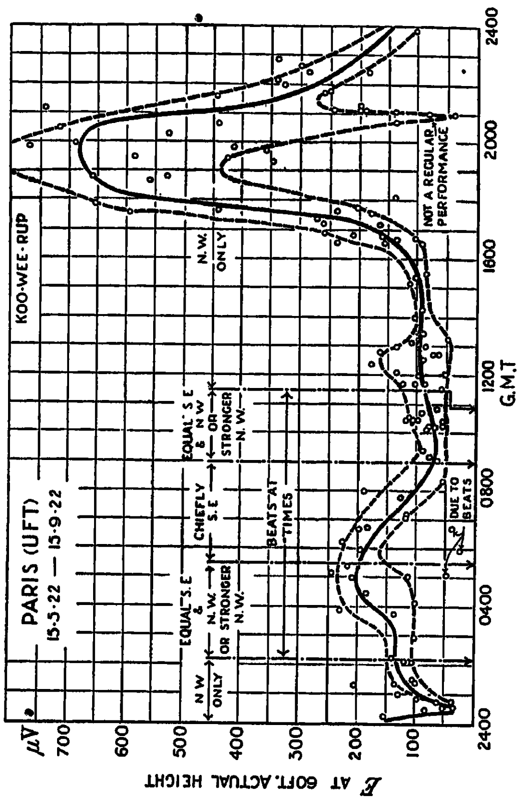


FIG. 35.
NOTE: Effective height = 12 metres.

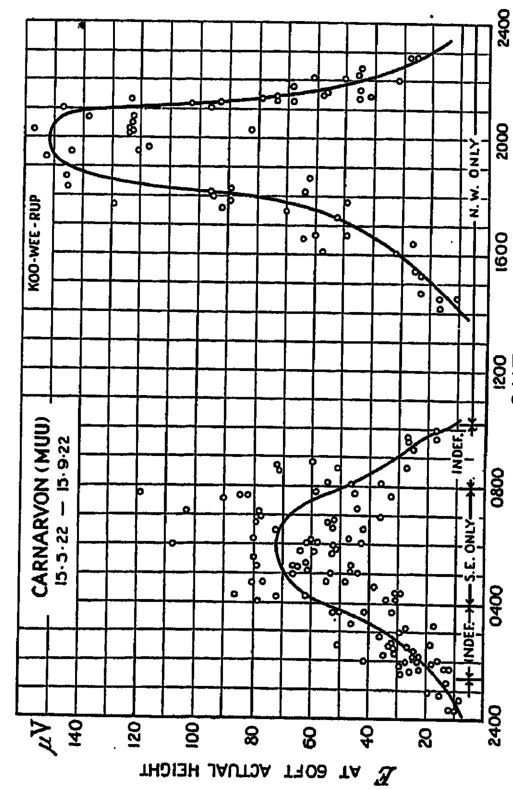


FIG. 36.
NOTE: Effective height = 12 metres.

"beats" do not necessarily occur when the signals received from the two opposite directions are equal in strength; and bad mutilation was often caused when the signals from one direction were quite weak compared that on Tuckerton is greatly reduced in comparison with the peak from the South-West, although Perth is not much more than 1 000 km from the antipodes of New York. Taking the shorter-wave stations, New Bruns-

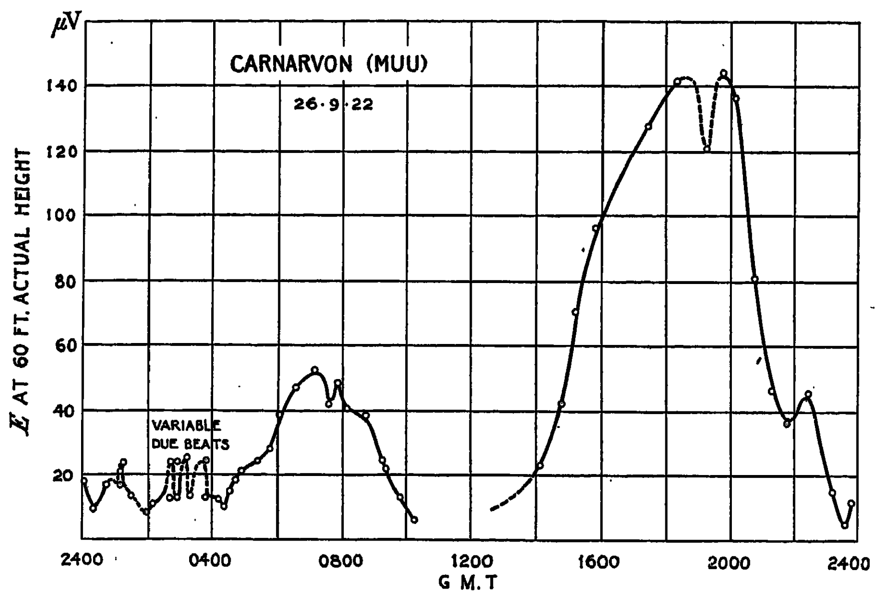


Fig. 37.—At Koo-Wee-Rup.
Note: Effective height = 12 metres.

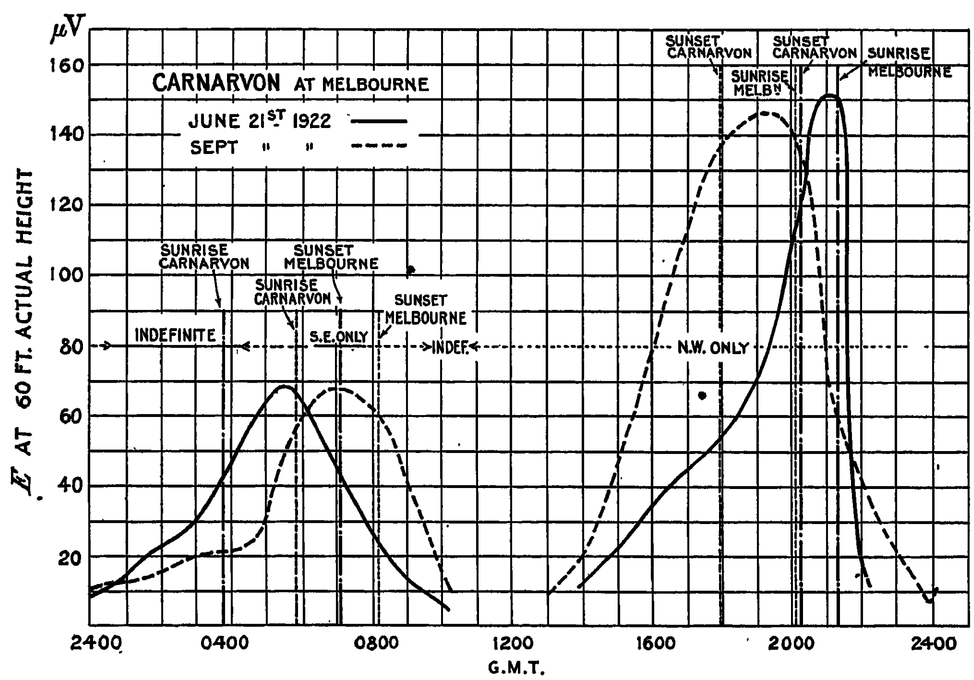


Fig. 38.—At Koo-Wee-Rup.
Note: Effective height = 12 metres.

with those from the opposite direction. Comparing the New York stations at Perth and at Melbourne, it will be seen that the peak on Rocky Point and Coram Hill from the North-East is almost non-existent, whilst wick and Marion, the peak on the former station from the South-West is actually lower than the peak at this time in Melbourne, and the latter station was never heard entirely from the South-West. In this connection

it should be noted that owing to the proximity of Perth to the antipodes of New York there was a difference of 20° or more between stations which, although generally spoken of under a general heading of New York stations, are actually some distance from New York. The bearing of Marion, for example, being only 30° East of North at Perth may introduce an effect which is in some manner connected with the East and West effect described elsewhere. Signals from Marion were not audible over a long enough period to enable sufficient data to be obtained for a curve. This also applies to KET (San Francisco). The latter station was heard on one occasion from the South-West, although for two or three hours during the all-dark period signals from the North-East were usually comparable with those heard at Melbourne. In general, although the all-daylight signals from the European stations were fairly constant, peak values of the all-dark signals were very variable.

Honolulu (Fig. 59) was heard from the South-West at certain times of the day, the signals from this direction being of equal strength to those from the North-East for about two hours of the day, but never stronger than those North-Easterly. The average all-dark signals from the North-East on this station were stronger at Perth than the average all-daylight signals, and although the all-daylight signals were considerably weaker than those at Melbourne, the all-dark signals were actually on an average as strong as, or stronger than, those at Melbourne, and, as at the latter place, signals reached a peak at sunrise at Honolulu.

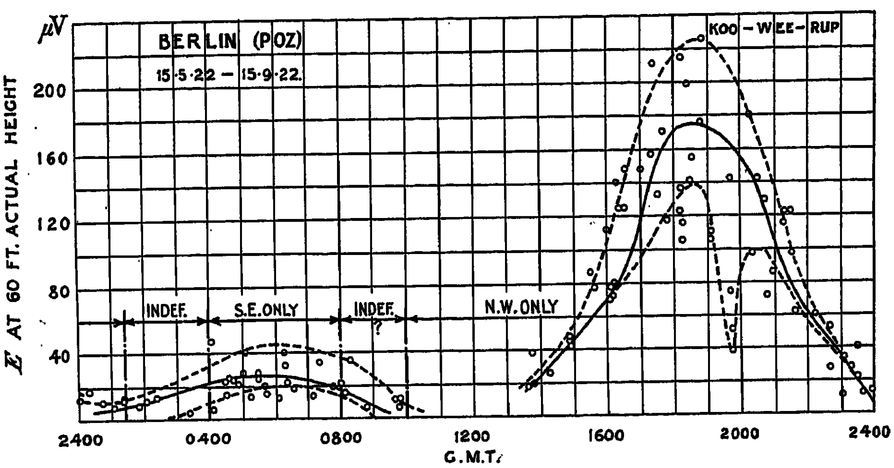


Fig. 39.
Note: Effective height = 12 metres.

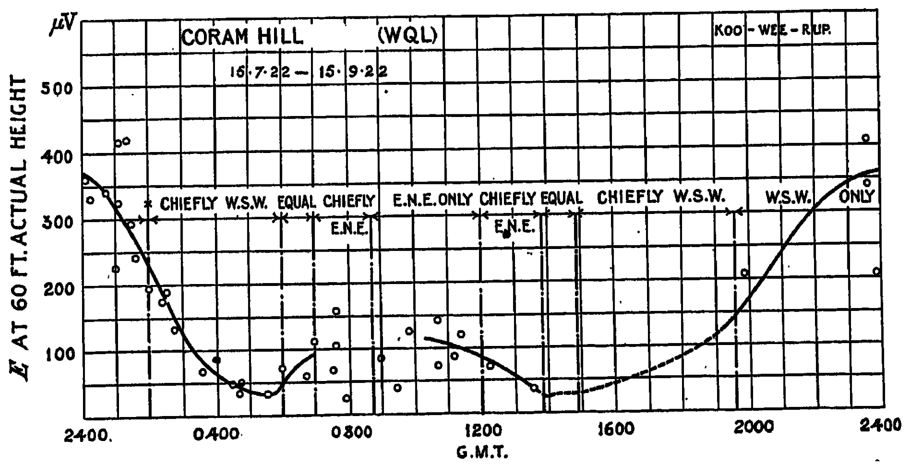


Fig. 40.
Note: Effective height = 12 metres.

Melbourne to London on S.S. "Boonah."

Figs. 60 to 79 inclusive give the attenuation curves for various stations obtained on the homeward voyage on the S.S. "Boonah," by way of Adelaide, Perth, Wyndham, Colombo and Suez. The figure at the beginning of this paper (see p. 934) shows the daily positions for the

outward and homeward voyages on the S.S. "Dorset" and S.S. "Boonah."

Fig. 67 for Leafield on 12 300 m shows a marked increase in signal strength near Colombo with the decrease

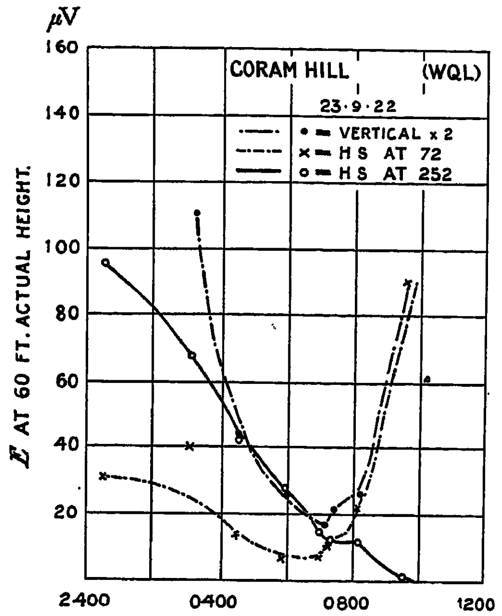


Fig. 41.—At Koo-Wee-Rup.

Note: Effective height = 12 metres.

in the amount of land traversed by the signals in India. This increase was noticed in this neighbourhood on other European stations.

Bordeaux (Fig. 61) was only using a wave-length of 18 000 m, so that no comparison could be made with signals from this station obtained on the outward voyage, during which the wave-length was 23 460 m. The beat effect was very marked on signals from Carnarvon (Fig. 65) whilst crossing the Australian Bight, and there was a period of several days along the North-West coast of Australia during which no signals were heard from this station.

The New York stations (Figs. 71 to 74 inclusive) were heard between Perth and Wyndham only from the South-South-West, and there was a period of several days between Wyndham and Colombo during which no signals were heard from the New York stations, this period corresponding to the time at which the great circle between the S.S. "Boonah" and New York was over or near the North and South Poles. The loss of signals over this period was probably due to the fact that under these conditions the signals have nearly always to traverse a path over which there is a mixture of light and darkness. The arrows show the direction from which the signals were received at the times observations were taken, assuming the top of the page to be North. The wave-length of Coram Hill (Fig. 71) was changed from 19 000 to 17 600 m shortly before leaving Australia.

Unfortunately, Rocky Point worked very little when all-daylight conditions intervened between the S.S. "Boonah" and this station, and it was not possible to obtain a curve from the few readings taken.

Honolulu (Fig. 75), as stated previously, was only received from the North-East at Melbourne, but was bi-directional for some hours a day at Perth. At Wyndham there were only occasional traces of signals from the South-West. Between Wyndham and Colombo signals were bi-directional for several hours a day with "beats," but after leaving Colombo signals were only from the West and later from the South-South-West. When this station was last heard in the Red Sea, signals were received from about North, the great-circle bearing being very near the Polar Circle, and although the distance was actually becoming daily less by this route, no further signals were heard.

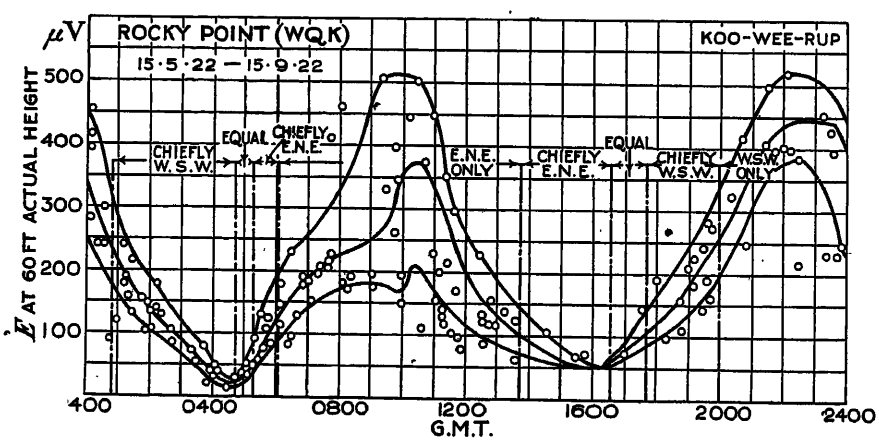


Fig. 42.

Note: Effective height = 12 metres.

Signals from Cavite (Fig. 76) were lost between Colombo and Aden, the attenuation being greater than for the West to East signals received from this station on the S.S. "Dorset." A portion of the attenuation curve obtained in the Pacific is given on this curve for comparison.

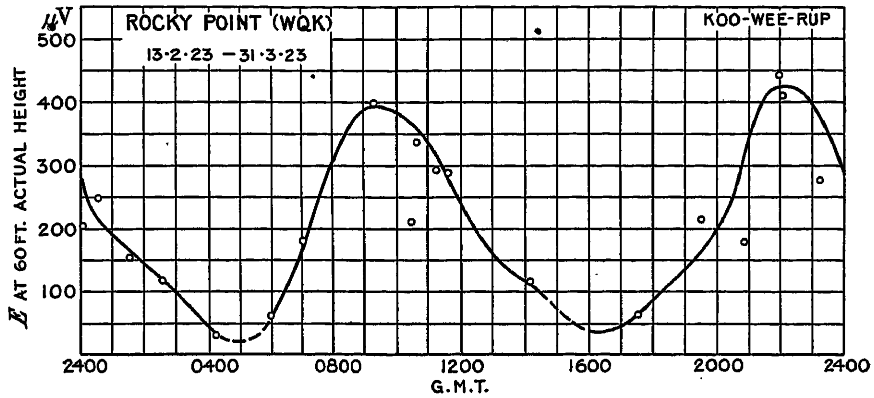


FIG. 43.
NOTE: Effective height = 12 metres.

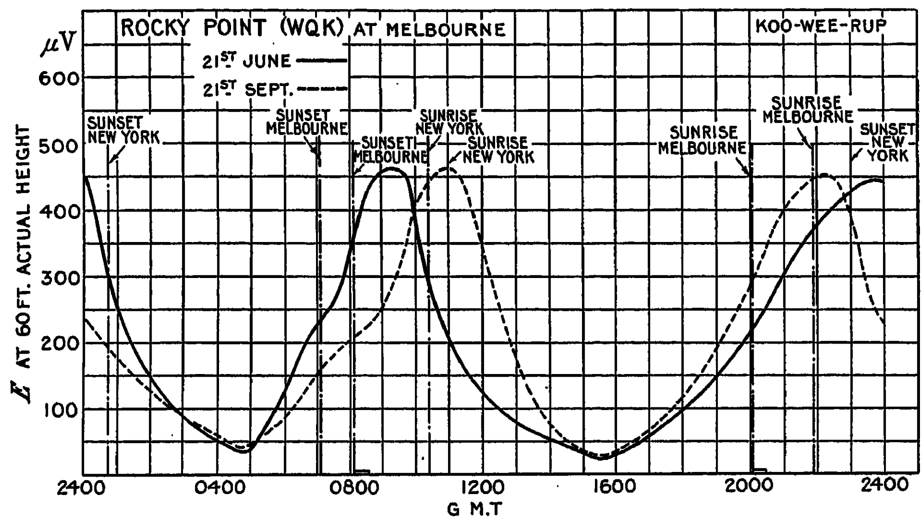


FIG. 44.
NOTE: Effective height = 12 metres.

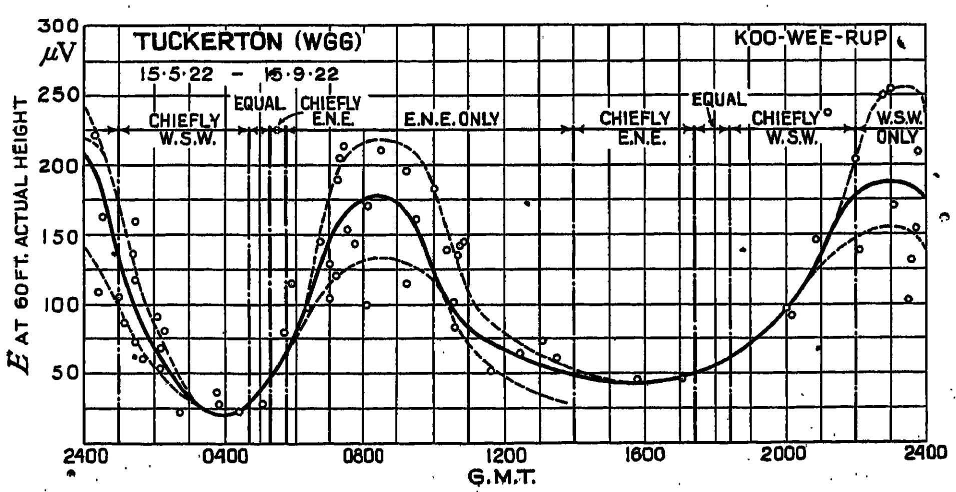


FIG. 45.
NOTE: Effective height = 12 metres.

General Observations.

Observations were also made both on the outward and homeward voyages and also in Australia, of the signal strength in microvolts per metre which would be required on various wave-lengths at any time and under the varying atmospheric conditions from day to day to ensure perfect readability.

The observed readability of various stations at these times was also estimated both on the vertical aerial and on the heart-shape receiver, so that the gain of the latter over the vertical aerial could be obtained at any time, this gain, of course, being dependent on the relative directions of signals and atmospherics. These results are not included in this paper.

Bearings of Signals.

Bearings obtained on the Bellini-Tosi direction finder in Australia on the long-distance stations, both in Europe and in America, were found to be remarkably accurate and constant. It was only on very rare occasions that any variation of bearing was observed due to the well-known night effect. Even during the change-over periods at times when signals were bi-directional, the bearing remained accurate and unchanged. The nearer stations such as Cavite suffered very much more from this night effect, and it was of fairly frequent occurrence on signals from Honolulu. This effect, which had been noted before this voyage was undertaken, frequently but not invariably occurred simultaneously

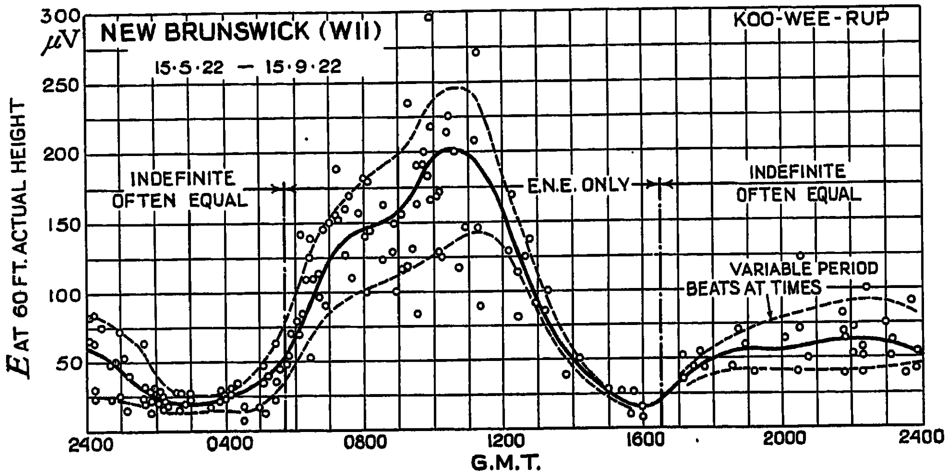


Fig. 46.

Note: Effective height = 12 metres.

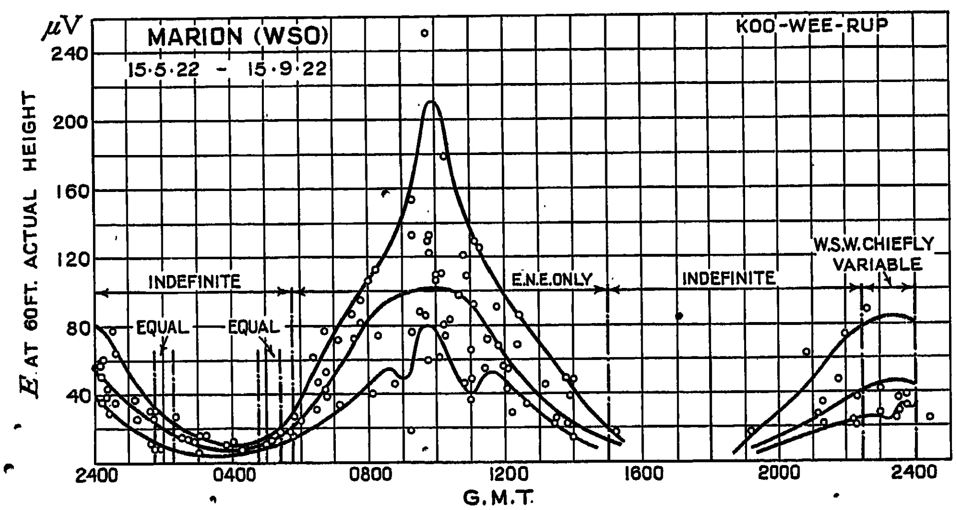


Fig. 47.

Note: Effective height = 12 metres.

with an increase or decrease of signal strength due to interference effects.

Day and Night Variations.

Fig. 80 gives typical curves of day and night variations. Generally speaking, it may be said that the all-daylight signals approximate to a straight line, provided that the daylight extends over a long enough period. When the hours of daylight become less, this straight line, as shown in Fig. 80, becomes a curve having a peak value at about midway between sunrise at one station and sunset at the other station. In the examples shown this is about half way between sunrise at the European station transmitting and sunset on the S.S. "Boonah."

There is always a minimum of signals at the times when it is half light and half dark between the transmitting and receiving stations. The minimum value reached by the signals at these times varies from day to day, but in some cases appears to be fairly constant. The all-dark values are very variable, and although it may generally be said that the all-dark signals at some time during the night will usually be greater than the

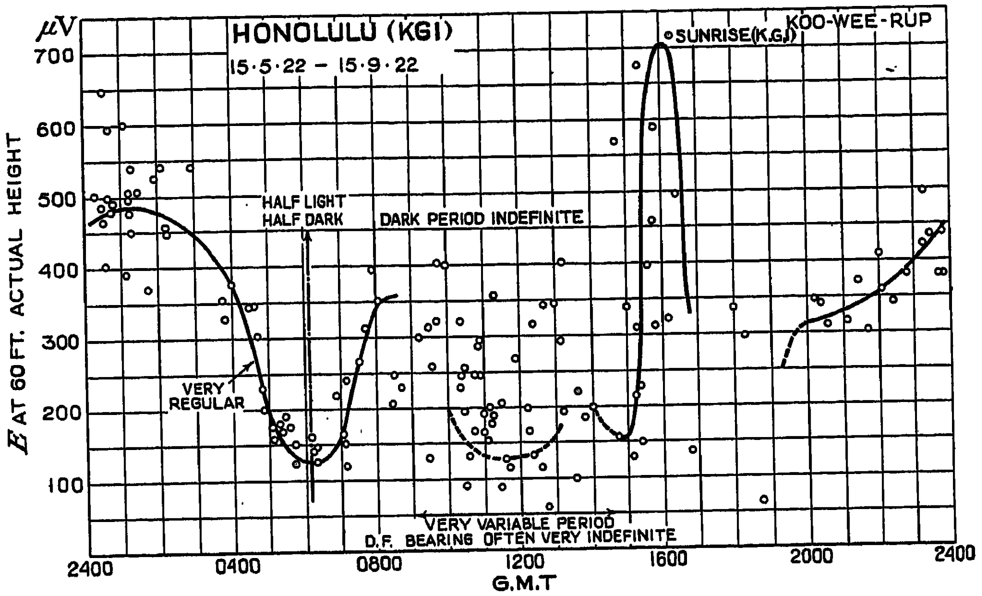


Fig. 48.

Note: Effective height = 12 metres.

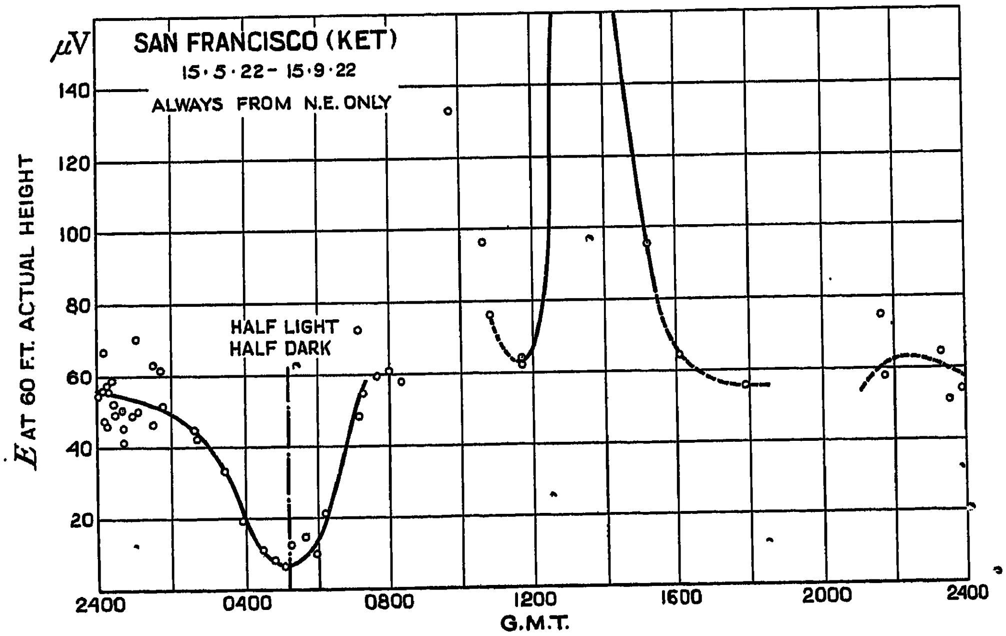


Fig. 49.—At Koo-Wee-Rup.

Note: Effective height = 12 metres.

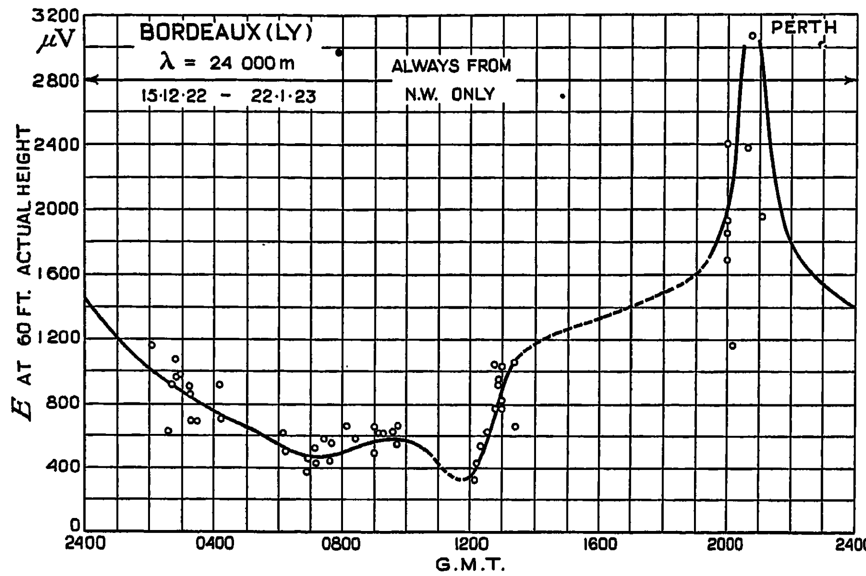


FIG. 50.

NOTE: Effective height = 12 metres.

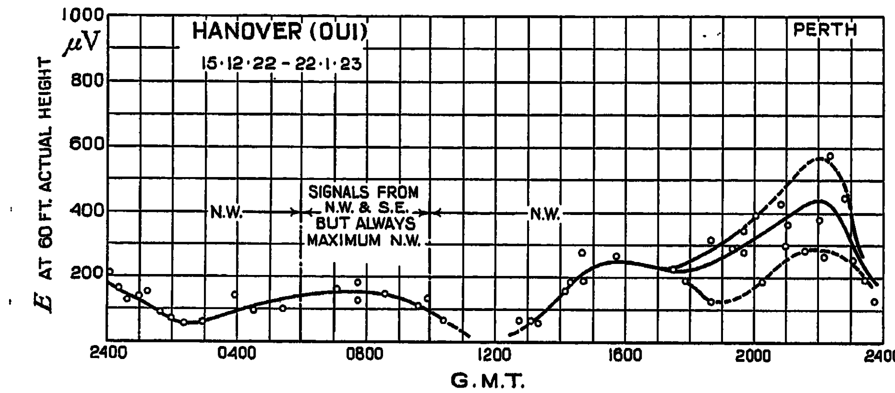


FIG. 51.

NOTE: Effective height = 12 metres.

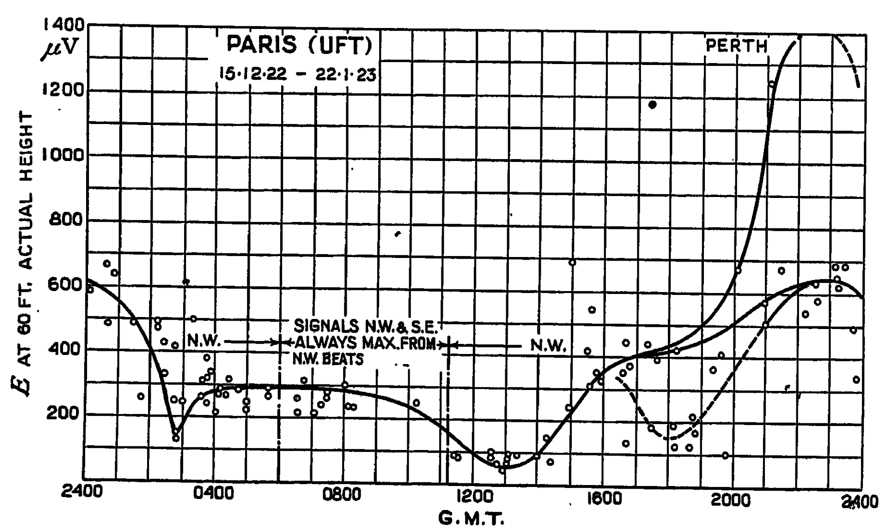


FIG. 52.

NOTE: Effective height = 12 metres.

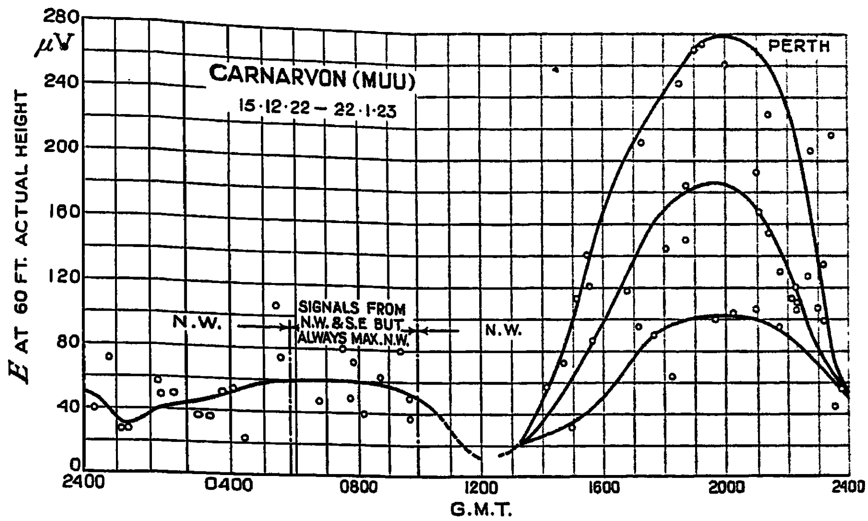


FIG. 53.

NOTE: Effective height = 12 metres.

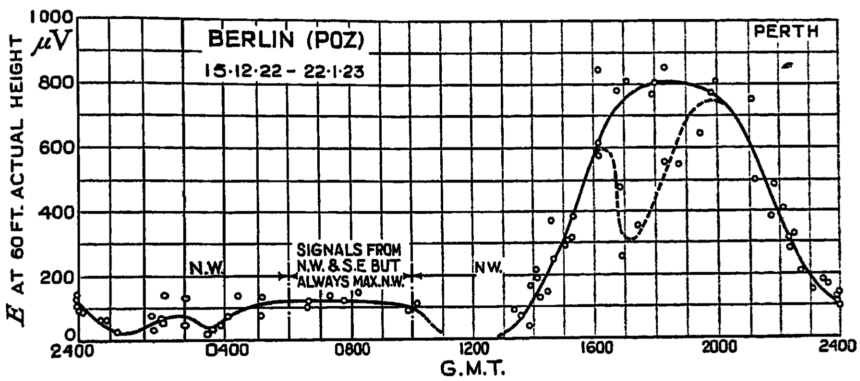


FIG. 54.

NOTE: Effective height = 12 metres.

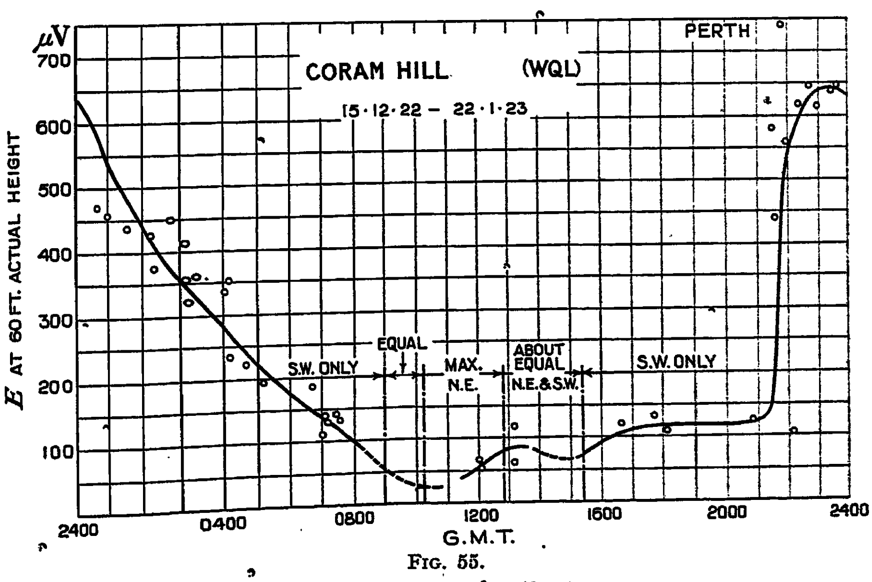


FIG. 55.

NOTE: Effective height = 12 metres.

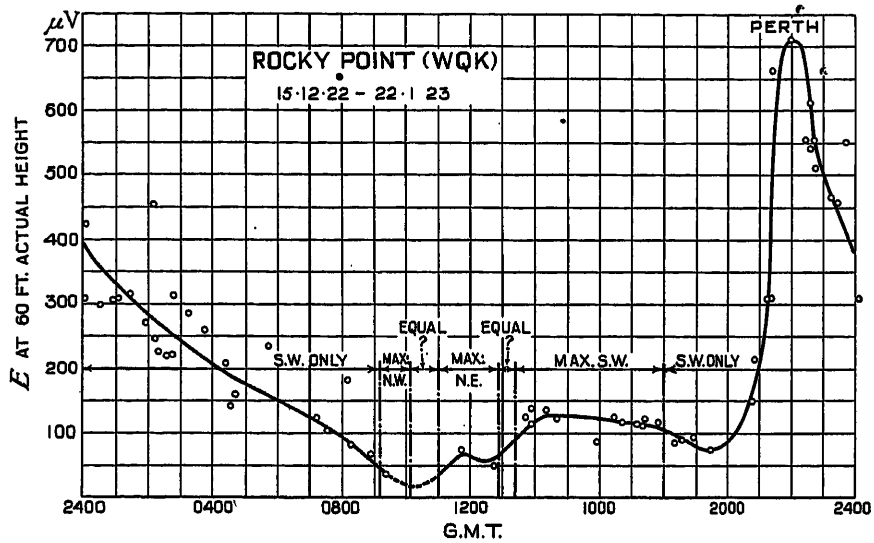


FIG. 56.

NOTE: Effective height = 12 metres.

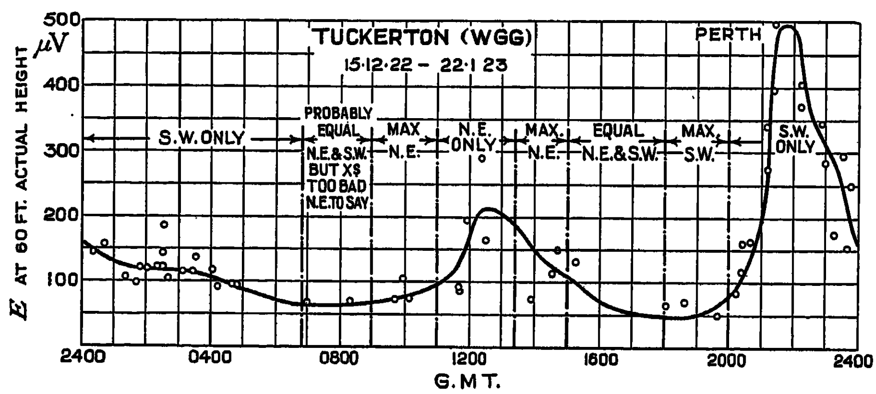


FIG. 57.

NOTE: Effective height = 12 metres.

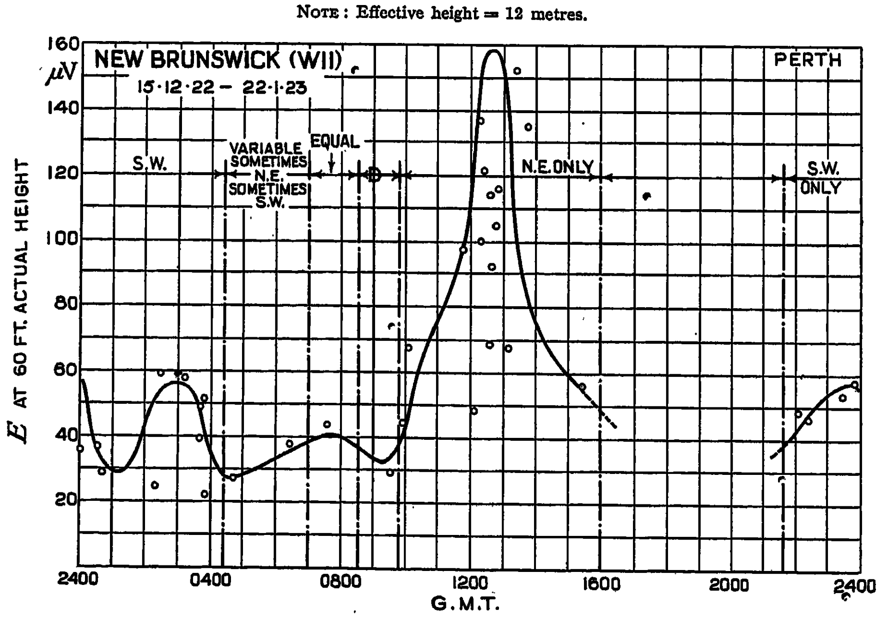


FIG. 58.

NOTE: D = doubtful. Effective height = 12 metres.

daylight signals, there are certain stations from which, at certain places, the average all-dark signal is consistently less than the all-daylight signal. There are some cases, e.g. Honolulu and San Francisco at Melbourne (Figs. 48 and 49), in which there is almost invariably a peak connected with sunrise at the transmitting station, and there are also examples of peaks of regular occurrence on other stations which appear to be connected definitely with sunrise at the receiving station; but as regards the all-dark period there appears to be nothing in any way definite, except possibly at very great distances such as the reception of the European stations at Melbourne, where it may be said there will always be a peak value at the all-dark period. At this distance, however, this period can hardly be termed an all-dark period, as sunset at the transmitting station is followed very shortly by sunrise at Melbourne, and conditions in this case do not appear to have time to become so unsettled. Although smooth curves have been drawn in most cases for these peak values at Melbourne and Perth, giving an average value over a long period of observations, more or less definite

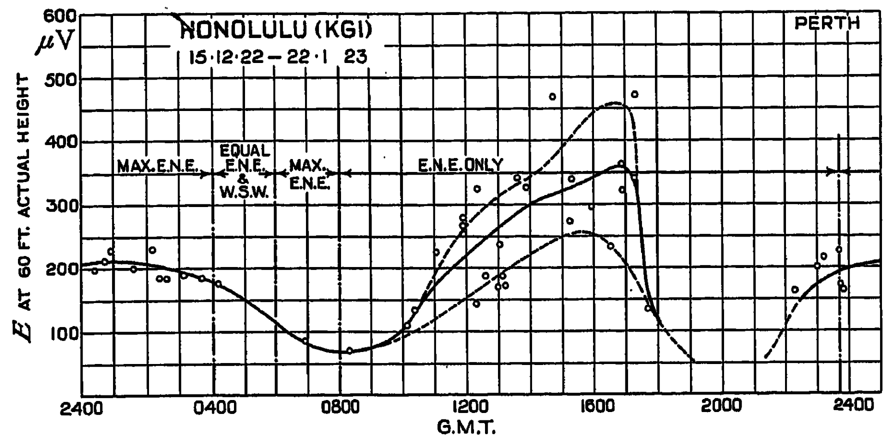


FIG. 59.

NOTE: Effective height = 12 metres.

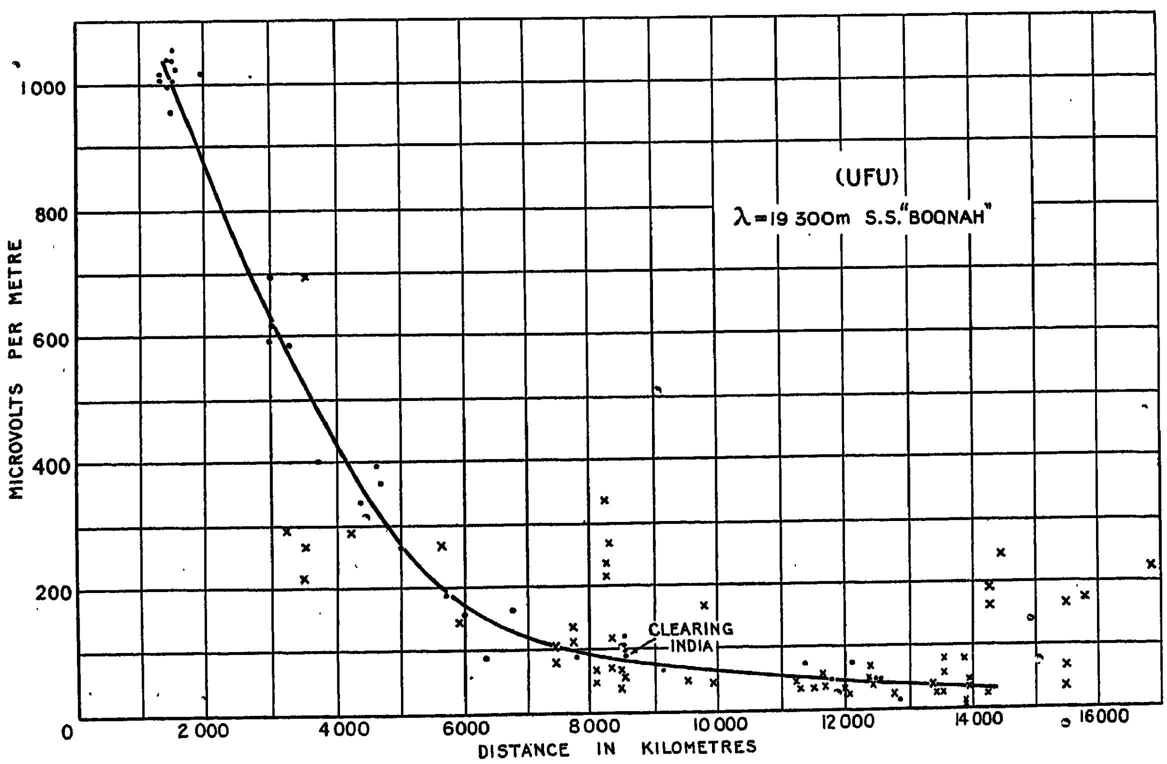


FIG. 60.

variations do occur during these peak times and may be attributed to local effects due to sunrise and sunset at the transmitting or receiving stations.

Effective Heights.

The effective height of the aerial on the S.S. "Dorset" was obtained both by calculation from the actual

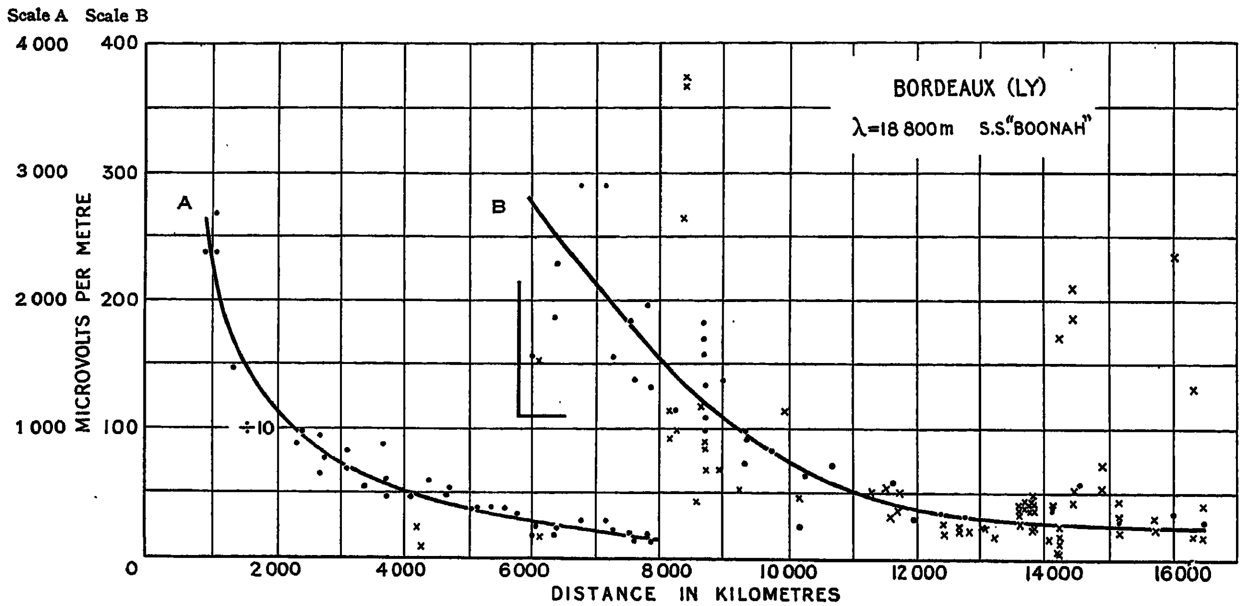


Fig. 61.

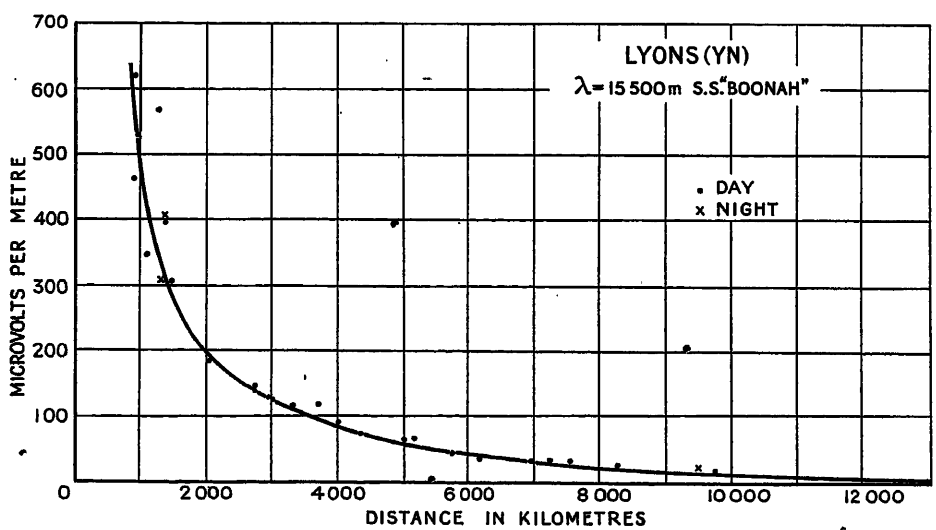


Fig. 62.

dimensions of the aerial, and also by a comparison of values of E.M.F. obtained of signals from the New York stations in the Irish Channel simultaneously with values obtained at Chelmsford, allowing for the absorption over England, the value of which had previously been found from tests made at Towyn, Poldhu, Girvan and Chelmsford. This effective height was taken as 12 m.

At Melbourne and Perth the aerials used were similar to an aerial of which the effective height had previously been obtained by experiment at Chelmsford. In these cases the height was again 12 m.

On the S.S. "Boonah" the effective height was obtained by calculation from the aerial dimensions, and also by a comparison of the E.M.F.'s measured on signals from the various stations with the values measured on shore at Melbourne, Perth and Poldhu, the S.S. "Boonah" being near these places on the homeward voyage. In the case of Poldhu, the American stations were used for the comparison. A value of 17·6 m was obtained for this aerial.

All distances on the voyage from Liverpool to Auckland have been worked out by Mr. Cunningham, Senior Wireless Officer of the S.S. "Dorset," and those on the

return voyage by Mr. Allnutt, who assisted in all experiments on the expedition.

Atmospherics.

Atmospherics were observed to be of two main types —clicks and crashes. The former have a sound similar to that produced in a receiver by a single lightning flash. Crashes may be of any duration from, say, 0·5 second to 5 seconds. The longer crashes lasting for several seconds appear to be connected with local temperature changes and squally weather, and were observed at Melbourne in the spring and autumn.

The term "grinders" has been applied to the continuous atmospherics noted chiefly in or near the tropics during the afternoon. Although there has been a tendency in the past to treat grinders as a type of atmospheric distinct from clicks and crashes, there is no doubt that these grinders are merely a very great number of clicks and crashes occurring together over a large area.

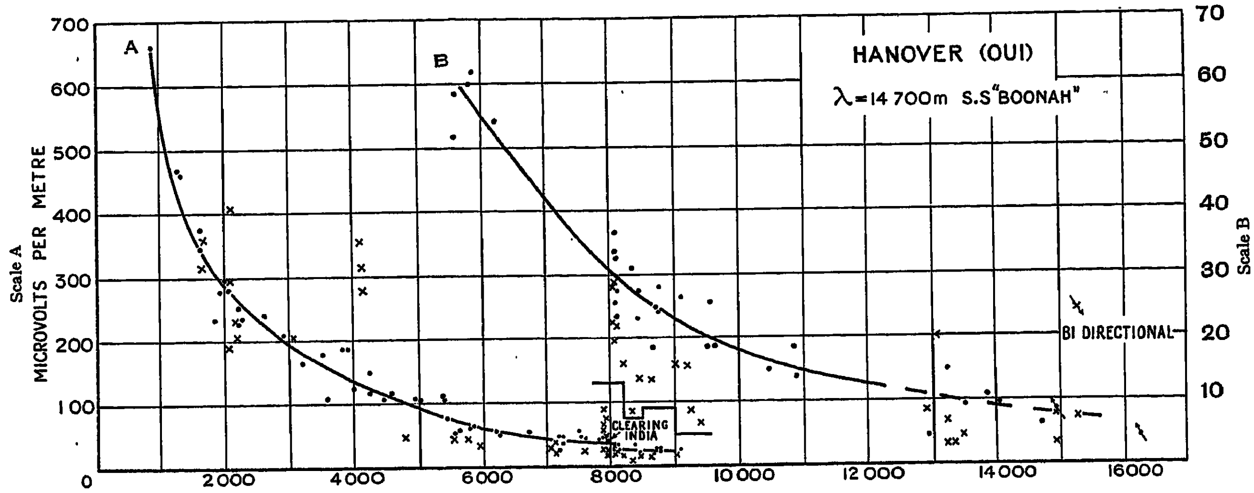


Fig. 63.

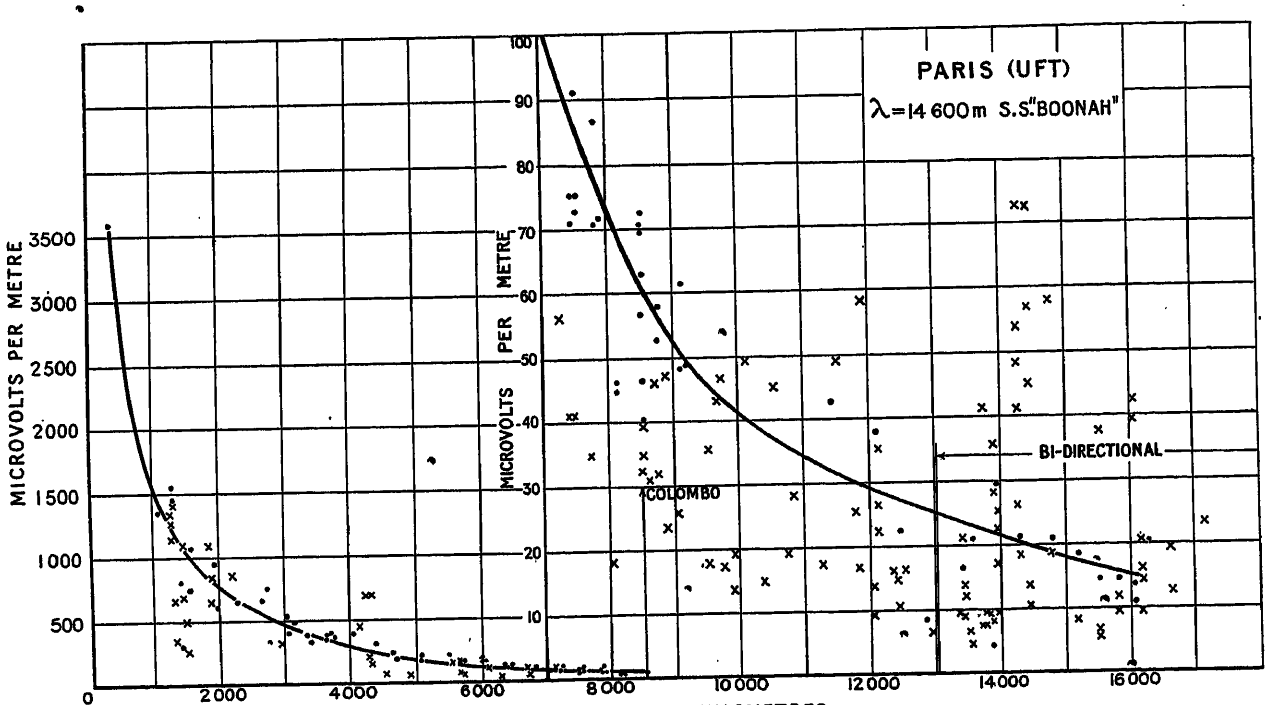


Fig. 64.

There is one other quite distinct type of atmospheric known as "fizzly" which often accompanies rain and hail squalls. This type produces a continuous hissing sound in the receiver, and is only present when showers of rain or hail having charged particles are near or actually in contact with the aerial.

It was found that, apart from purely local storms which may occur in any part of the world from day to day and at any time of the day, atmospherics were always produced over large areas of land in or near the

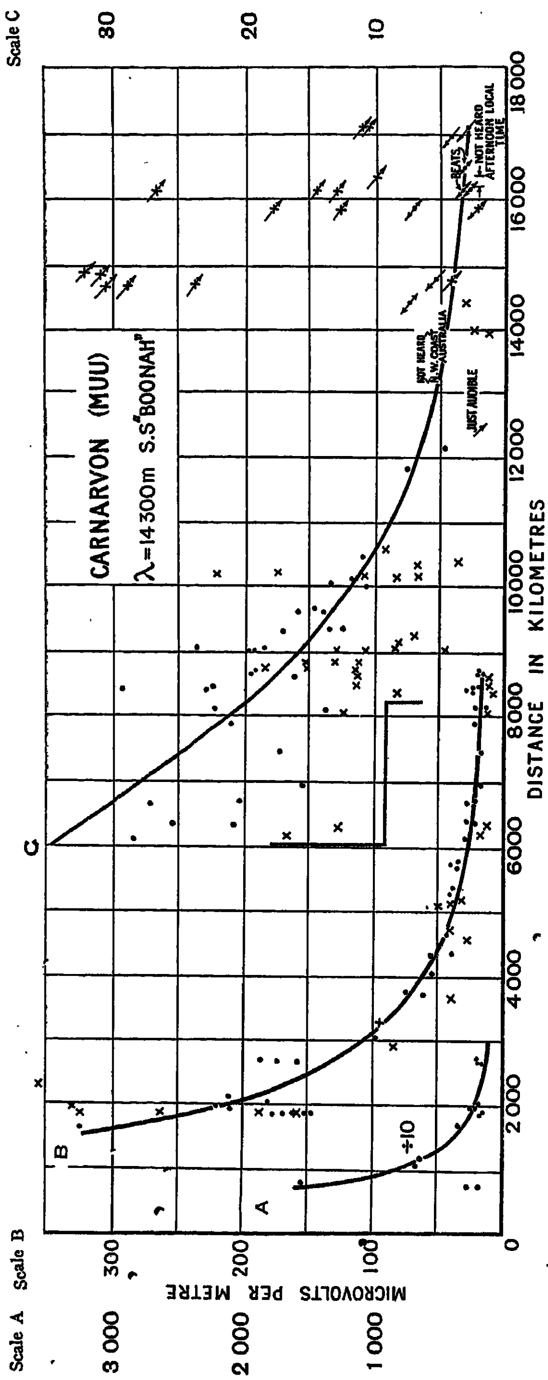


Fig. 65.

tropics. The number of these atmospherics produced over these land areas reached a maximum at about 3 p.m. local time at any place in those areas, the numbers decreasing towards sunset, reaching a minimum in the early hours of the morning and increasing again to the maximum about 3 p.m., when continuous atmospherics or "grinders" were heard. The place of origin of these grinders was observed to vary with the seasons, being in the Northern hemisphere during the summer in that hemisphere, and in the Southern hemisphere during the summer in the Southern hemisphere. During the Northern summer these grinders are mostly produced in Northern Africa, Arabia, India, Burma, Siam, the South of China, Mexico, and South America North of the equator.

During the summer in the Southern hemisphere the majority of the grinders originate in Southern Africa, Australia and South America. The numbers produced appear to be proportional to the area of the tropical land, and no grinders are produced over the oceans.

On the homeward voyage of the S.S. "Boonah," during the summer in the Northern hemisphere, a large number of bearings were taken showing very clearly the movement of these grinders westward with the sun. The bearings shown on each map were all taken at about the same G.M.T. on various days during the voyage and have been corrected for the great circle. All the bearings in Fig. 81 were taken between 0700 and 0800 G.M.T. and show the origin of the "grinders" to be in Southern China when it is about 3 p.m. there. The clicks at this time are only few in number and indefinite in the Mediterranean where it is early morning, but are increasing in numbers in Persia and Northern India with the approach of the grinders, which are seen at their 3 p.m. maximum in Afghanistan some three hours later (see Fig. 82).

By this time the clicks are decreasing in numbers in Southern China after the passing of the grinders' maximum there. Fig. 83 shows the conditions some three hours later when the grinders in Northern Africa are at their height, and Fig. 84 some seven hours later shows the grinders' origin in the North of South America and Central America. It is not easy to observe the South American grinders until the decrease with night of the clicks and crashes from Northern Africa, which, at this time of the year, is an enormous atmospheric-producing centre. After the American grinders there are no more produced until 0700–0800 G.M.T., when the cycle is repeated, commencing again with Fig. 81, this absence of grinders from about midnight until 0700–0800 G.M.T. being due to the absence of land areas in the Pacific Ocean.

Bearings obtained on the grinders at Melbourne and Perth during the Australian summer intersected about the centre of tropical Australia, as shown in Fig. 81, during the afternoon there. These Australian grinders became less and less towards sunset, the clicks and crashes forming them becoming less and less in number during the night and finally reaching a minimum about sunrise. With the diminution of these Australian grinders, a further series of grinders was heard from the direction of South Africa (see Fig. 83), reaching a maximum frequency about 3 p.m. local time in South Africa.

The results just described were obtained during December–February at Perth and Melbourne. Between midnight and 0700 G.M.T. small continuous atmospherics were frequently observed at Melbourne in a South-

Easterly direction, and there is not much doubt that these atmospherics originated in the North of South America. These South American atmospherics were less in numbers than at their 3 p.m. maximum some hours previously, but became more noticeable at Melbourne with the increase of darkness between Melbourne and South America over the Pacific. It was found that atmospherics increased in strength with darkness in the same manner as signals, and in several instances there appeared to be fading periods on atmospherics at a time when half-light and half-dark conditions intervened between the receiving station and the source of the atmospherics. This fading would not be as marked as that on the signals, due probably to the fact that the atmospherics originated over a large area and would not all reach a minimum at the same time.

than on the shorter wave-length of, say, 10 000 m. This fact was an additional aid in the separating of the various sources. In the same manner, at times at Perth when the Australian atmospherics and the longer-distance African atmospherics were present simultaneously, a bearing taken on atmospherics on 10 000 m would be North-East and one taken on 20 000 m would be South-West, the near-by atmospherics predominating on the shorter waves, and the longer distance predominating on the longer wave-lengths. Generally speaking, a lengthening of the wave-length enabled atmospherics to be heard from over a larger area. The bearing on the unidirectional receiver on a near-by atmospheric-producing centre covering a large area was always less definite than that on a similar source at a great distance; and the most difficult conditions for observations were when

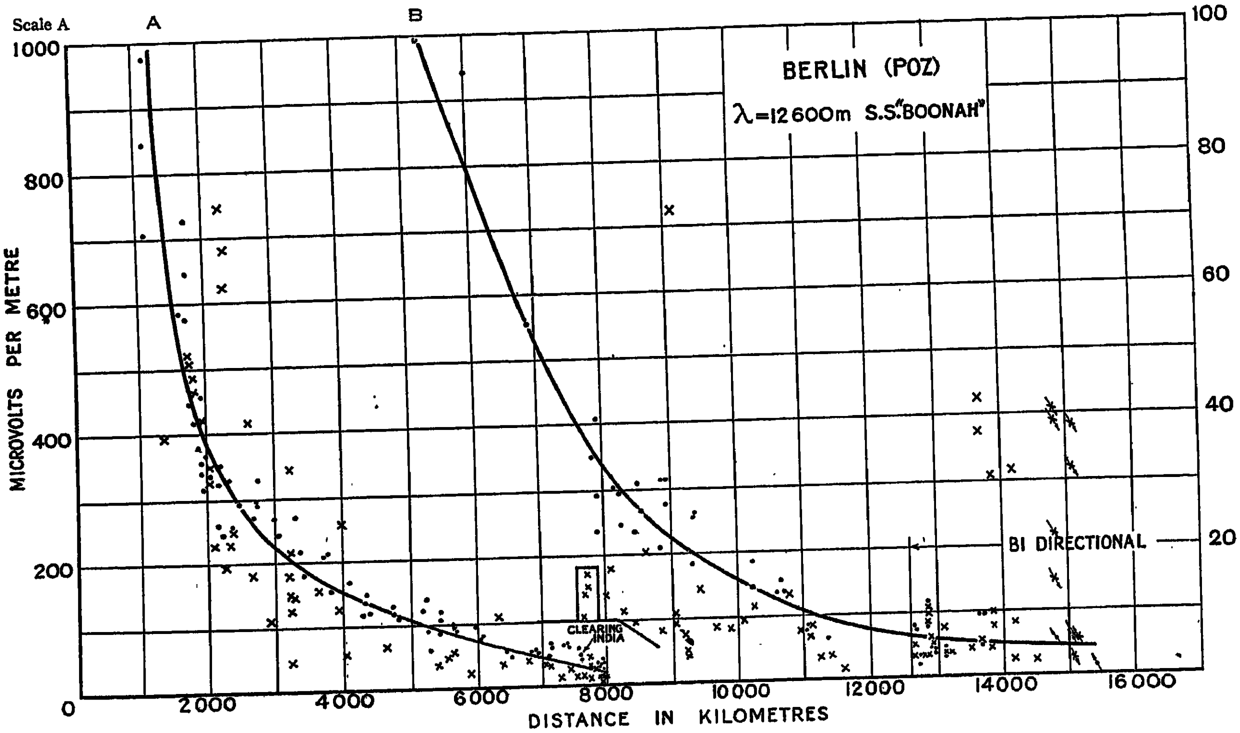


FIG. 66.

These South American atmospherics heard at Melbourne, being opposite in direction to those from the Australian Continent, were difficult to distinguish from the latter on the unidirectional receiver, as on rotating the moving coil of this receiver to what would be the minimum of one source of atmospherics, atmospherics from the opposite source are received at maximum intensity, or, in other words, there is no minimum obtainable at any position of the rotating coil. This also applies to the African atmospherics received at Perth. The existence of the two sources may, however, be proved by the fact that the bearing or minimum on the frame or bi-directional receiver is very marked at these times, whereas the bearing or minimum on the unidirectional receiver is almost non-existent. These atmospherics received from great distances were always more marked on the long wave-lengths of the order of 20 000 m two sources were present simultaneously in directions at right angles. Under these conditions it was only possible to distinguish the two sources by some difference in the sound or the frequency of the atmospherics from the two sources. The maximum intensity of the African atmospherics received at Perth was found to be some two or three hours after their maximum frequency at 3 p.m. in Africa, or at a time when darkness extended between Perth and Africa.

Information regarding the microvolts per metre required to read through atmospherics in various directions was obtained on the unidirectional receiver at Melbourne and Perth, and also by another expedition in South America, and ratios were obtained of these readabilities in various directions at different times of the day. These results have not been published in this paper. In similar work carried out by the

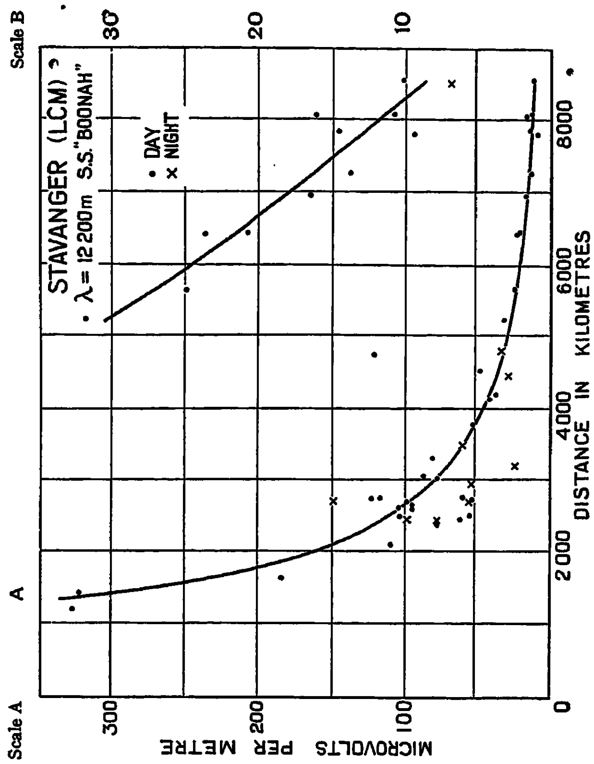


FIG. 68.

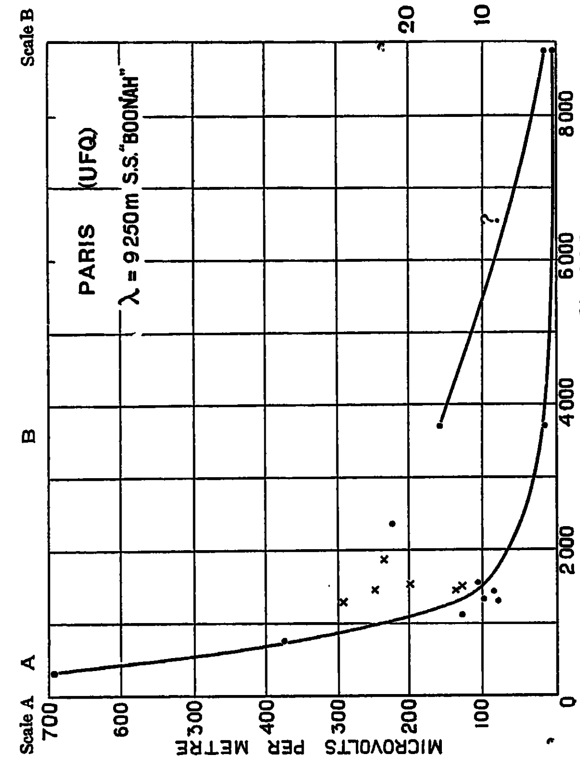


FIG. 70.

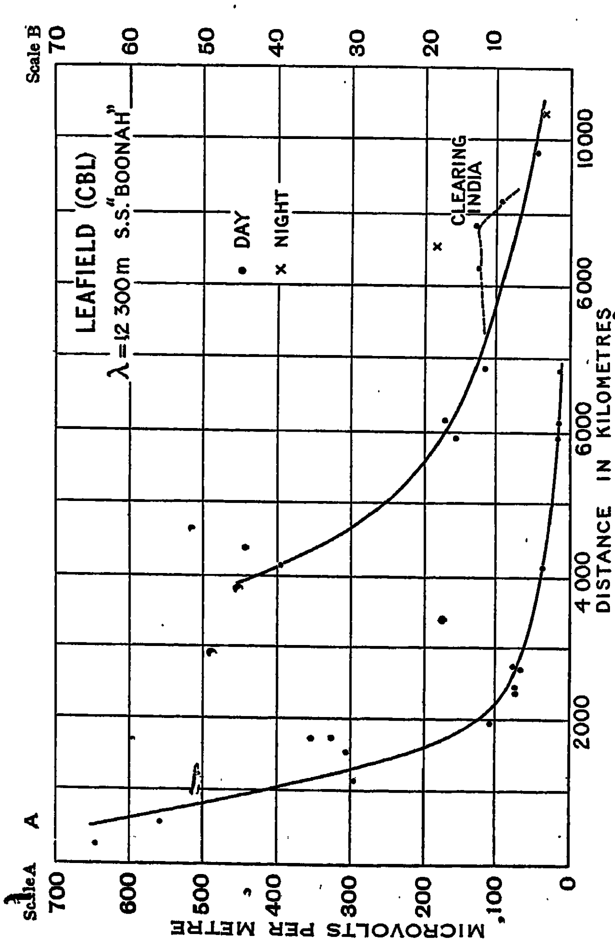


FIG. 67.

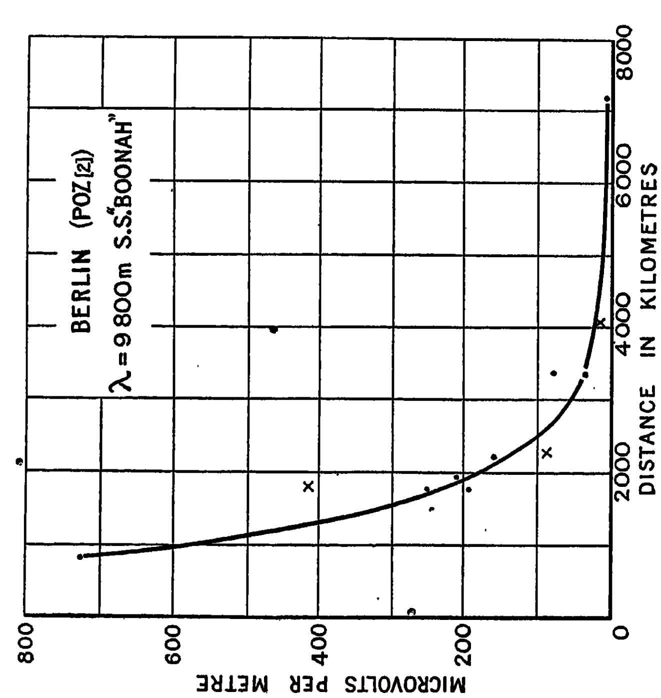


FIG. 69.

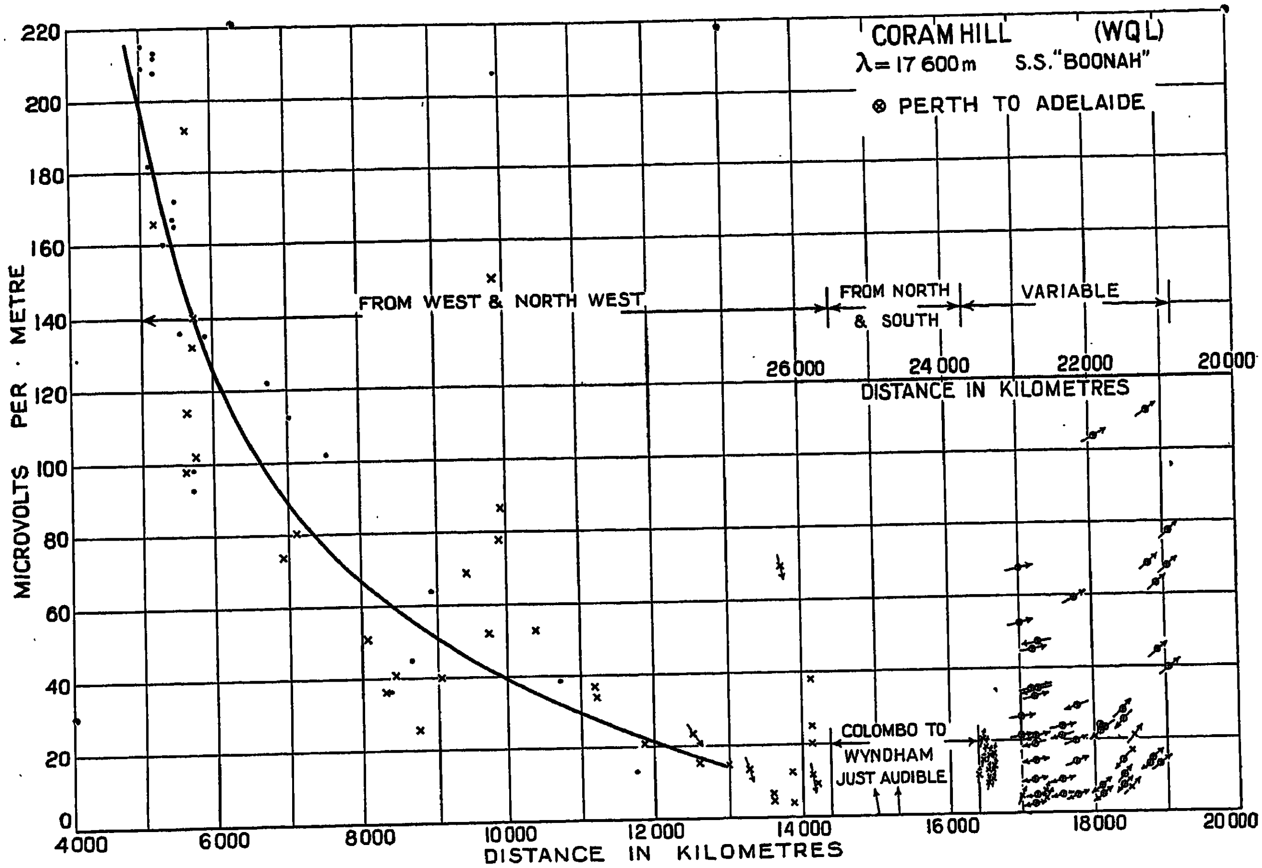

CORAM HILL (WQL)
λ= 17 600 m S.S. "BOONAH"
⊗ PERTH TO ADELAIDE
FROM WEST & NORTH WEST
FROM NORTH & SOUTH
VARIABLE
26 000
24 000
22 000
20 000
DISTANCE IN KILOMETRES
COLOMBO TO WYNDHAM JUST AUDIBLE
MICROVOLTS PER METRE
220
200
180
160
140
120
100
80
60
40
20
0
4 000
6 000
8 000
10 000
12 000
14 000
16 000
18 000
20 000
DISTANCE IN KILOMETRES

FIG. 71.

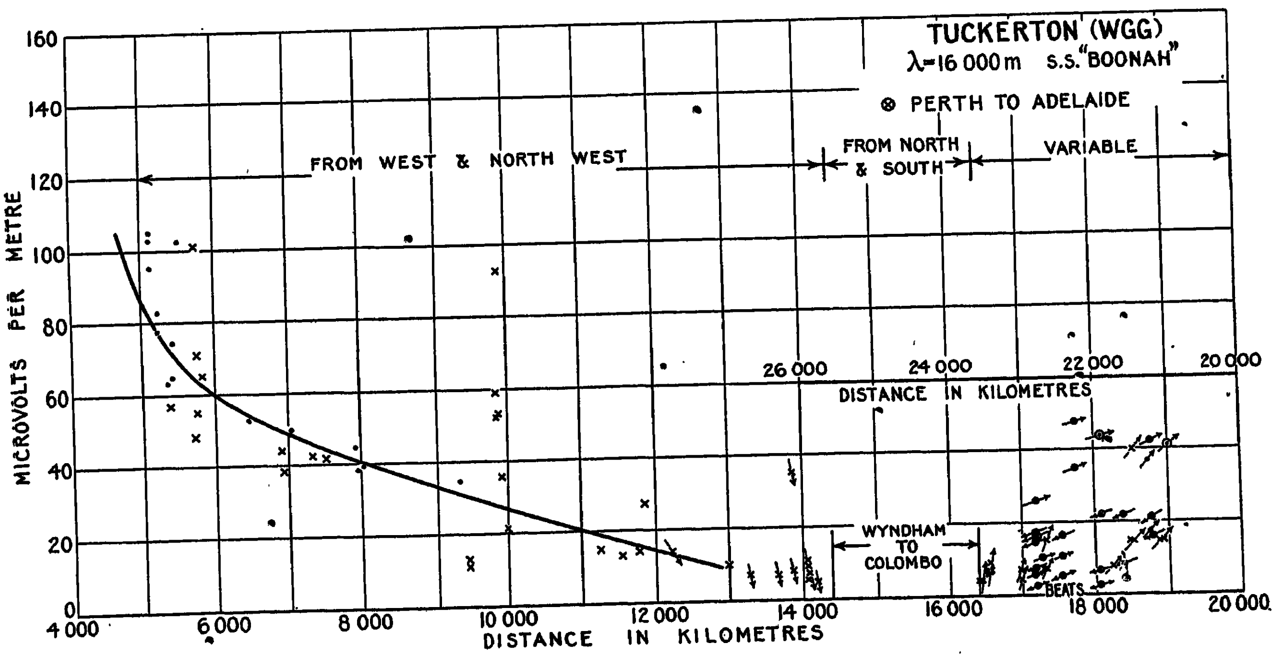

TUCKERTON (WGG)
λ=16 000 m S.S. "BOONAH"
⊗ PERTH TO ADELAIDE
FROM WEST & NORTH WEST
FROM NORTH & SOUTH
VARIABLE
26 000
24 000
22 000
20 000
DISTANCE IN KILOMETRES
WYNDHAM TO COLOMBO
BEATS
MICROVOLTS PER METRE
160
140
120
100
80
60
40
20
0
4 000
6 000
8 000
10 000
12 000
14 000
16 000
18 000
20 000
DISTANCE IN KILOMETRES

FIG. 72.

expedition to South America, the African and South American sources of atmospherics were very clearly marked. This expedition recorded local origins of atmospherics in the mountains near Rio. In Australia, on occasions, the mountains of the Dividing Range

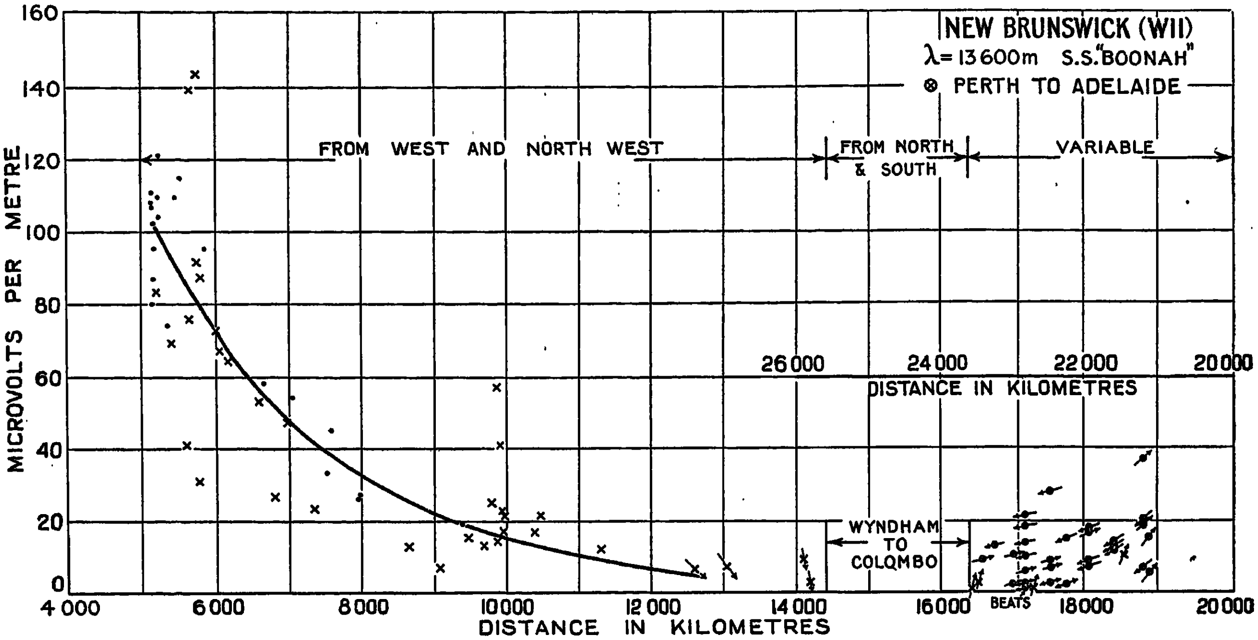


FIG. 73.

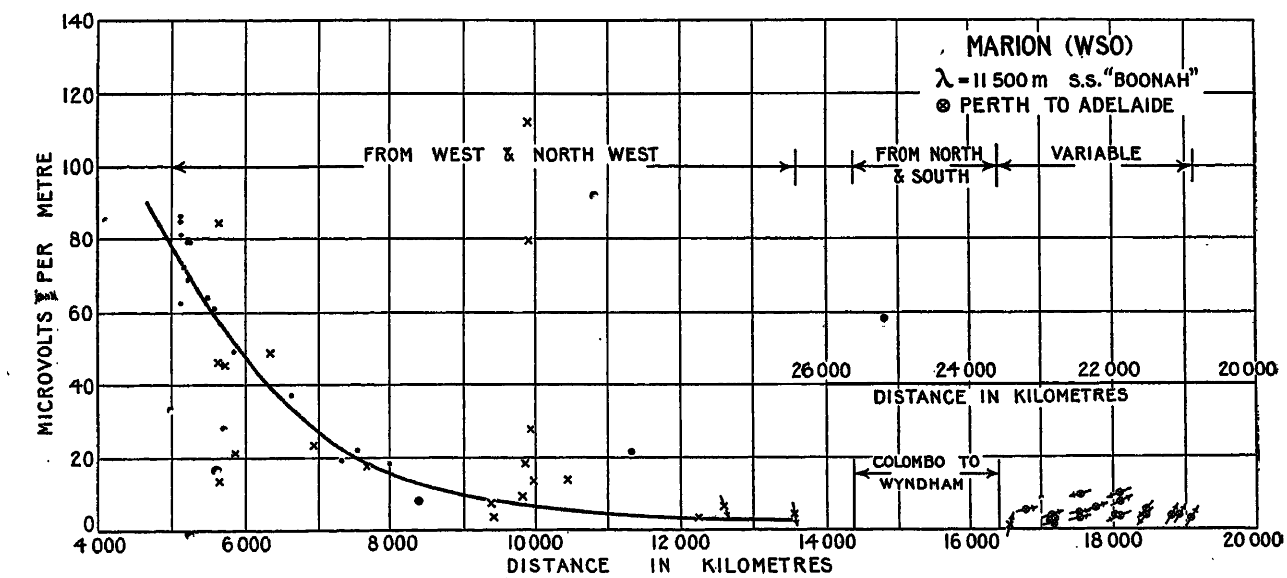


FIG. 74.

in the neighbourhood of Sydney appeared to be the origin of bad local clicks. These local clicks were also observed in the neighbourhood of Java on the return journey, and in the neighbourhood of the Abyssinian mountains, both of which districts are known to be thunderstorm centres. It was found in general that a local thunderstorm did not affect the readability of weak signals to the same extent as near-by grinders. Whereas in the former case letters would only be obliterated at intervals by lightning flashes, in the latter case all traces of the signals would often be entirely buried by the continuous grinders. Local storms at Melbourne appeared to be most prevalent during the spring and autumn at the change of seasons, and their effects were superimposed on the regular diurnal changes occurring in the grinders, differing from the latter in that they might occur at any time and in any direction.

Figs. 85 and 86 show the diurnal variations in the bearings of atmospherics as noted at Rio de Janeiro by the party observing there, and by the Australian party at Melbourne and Perth. These bearings are for the month of February when the sun is in the Southern hemisphere. At midnight G.M.T., 3 p.m. local time in the Pacific, there is no grinder maximum, and there are the remainder of the clicks at the South American centre and a few from the African centre. In Australia the clicks from the local centre are very few due to its being early morning there, and the remainder of the African clicks from the whole of that centre received at Perth and Melbourne as small continuous clicks are decreasing with the extension of daylight over the Indian Ocean.

At 0300 G.M.T. the production of atmospherics is at a minimum in Africa with sunrise there, and nothing is heard from the latter centre either in Australia or Rio. In Australia the clicks are increasing with the approach of 3 p.m., and at this period small continuous atmospherics are frequently observed from the direction of South America where the clicks are still in evidence.

At 0600 G.M.T. the Australian grinders are at their maximum. The small continuous clicks are still audible from the South American centre as darkness extends over the Pacific, but these clicks are becoming less with the approach of sunrise in South America, until finally at sunrise there, at 0900 G.M.T., they disappear. By this time the grinders are becoming less in Australia and are commencing in Africa. By 1200 G.M.T. the Australian grinders are decreasing and thinning out into less and less continuous clicks, and the small African grinders, which by this time are near their frequency maximum, become noticeable in Australia and Rio. At the same time the clicks are increasing at the South American centre. At 1500 G.M.T. rather similar conditions prevail, but the Australian clicks are fewer though of greater intensity due to night propagation; the African grinders are of greater intensity also due to the increase of darkness, and the South American clicks are developing into grinders which reach a maximum about 1800 G.M.T. The African grinders are now less in numbers but at their maximum intensity in Australia, due to its being dark all over the Indian Ocean. By 2100 G.M.T. the Australian clicks are at their sunrise minimum of production, the African small continuous atmospherics are still in evidence, and the grinders at the American centre are decreasing. The latter are not yet noticeable at Melbourne, due probably to the fact that it is daylight all over the Pacific.

Attenuation.

In developing a theory to explain this mass of material, the variability of the data should always be borne in mind.

It is not possible to say that the signal strength at a given place will remain constant even when all the known factors, such as aerial transmitting current, effective height, nature of the intervening ground, etc., remain constant.

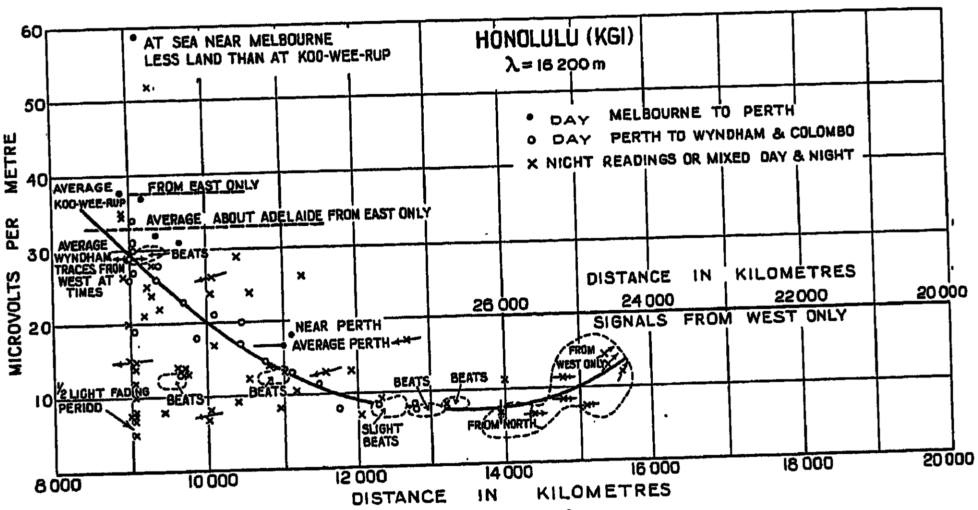


FIG. 75.

Apart from the more or less regular diurnal changes, there are accidental changes which may in certain cases amount to a large fraction of the mean E.M.F. to be measured.

This accidental variation is, as is well known, especially great when the ray lies entirely in the dark hemisphere, and for this reason it is necessary to obtain a very large number of night readings before they can be reduced to order. As it was impossible to keep a regular 24 hours' watch on the trip, the night readings obtained must be regarded merely as samples from which only little information can be obtained.

Day readings, on the other hand, are very much steadier, and although at great distances there is a very marked diurnal change (even when the ray is wholly in light), isolated values do not vary from the mean to an extent comparable with the night readings. In general the mean day value will be chosen for comparison with the

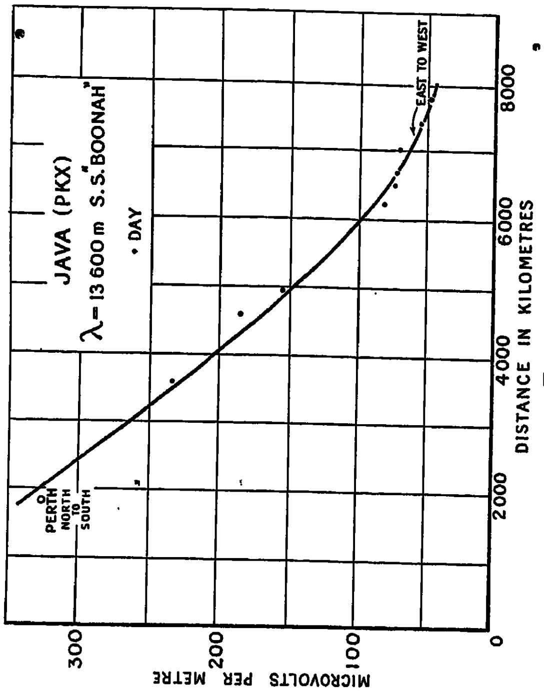


FIG. 77.

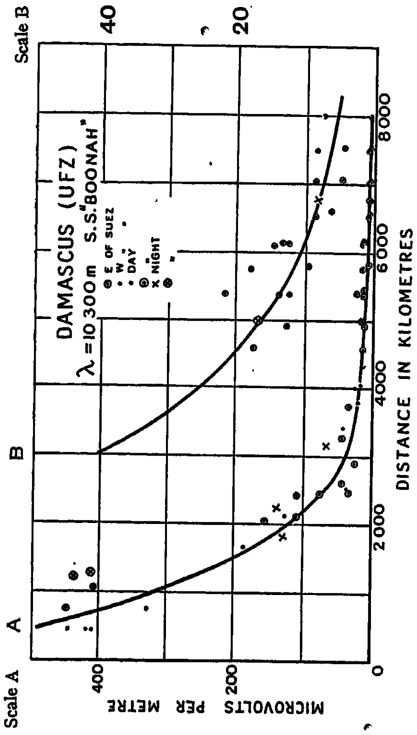


FIG. 79.

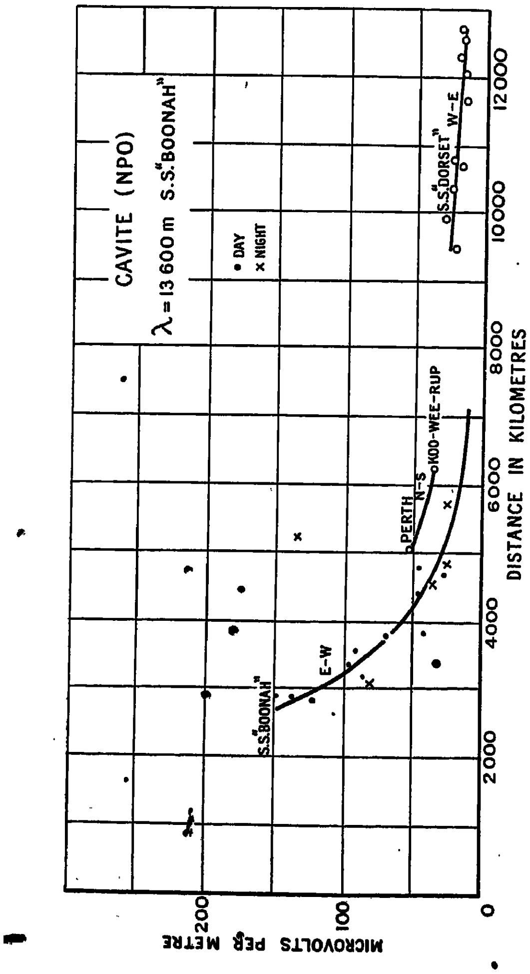


FIG. 76.

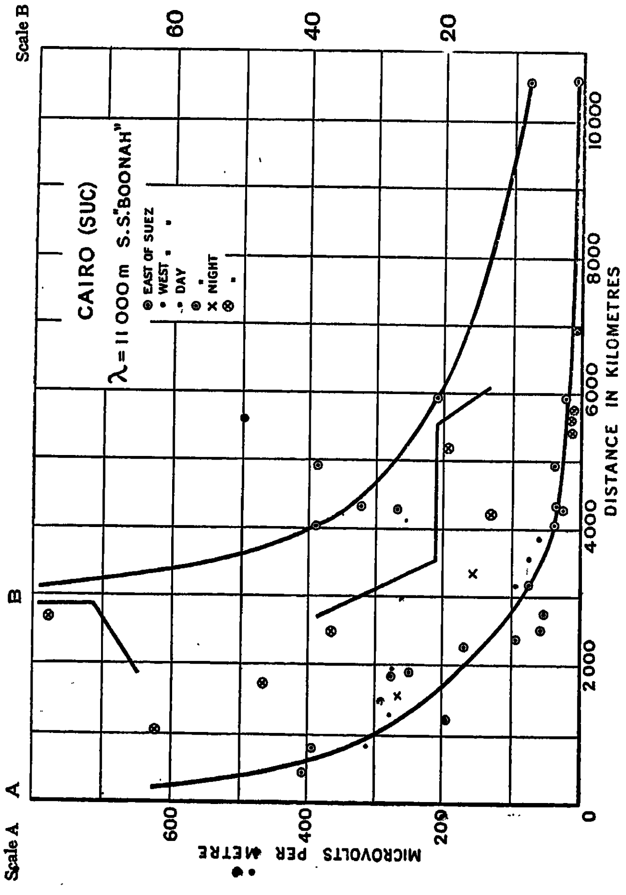


FIG. 78.

theoretical value, except where otherwise explicitly stated. It is well to emphasize the fact that isolated observations should be viewed with distrust.

In the case of the attenuation curves the values taken from a smooth curve passing through all the day readings will constitute the observed value. A certain amount of latitude in drawing the smooth curve is possible, of course, but the accuracy of the results does not warrant any elaborate mathematical process for determining this mean curve exactly, and the labour entailed would be prohibitive.

Choice of comparison formulæ.—In our opinion there does not seem to be very much doubt about the choice of formula for comparison.

Although Austin's formula, which expresses the signal E.M.F. in the form

$$E \text{ (in volts per cm)} = \frac{120\pi h I e^{-\alpha d/\sqrt{\lambda}}}{\lambda d}$$

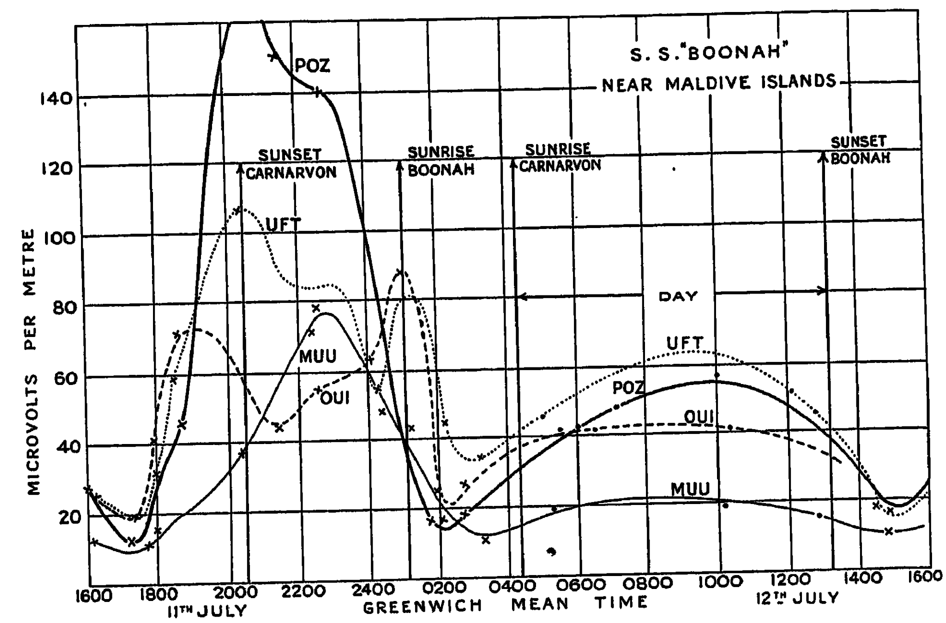


FIG. 80.

has received the sanction of use, it is admittedly of a semi-empirical nature, and although it might be useful as a means of calculating signal E.M.F.'s it can give no information with regard to the nature of the transmission of signals, beyond the fact that it either agrees or does not agree with the observed facts. On the other hand, we have in the work of G. N. Watson two very explicit formulæ, which we may call the diffraction and reflection formulæ respectively, from which a great deal of information may be derived. These two formulæ enable one to calculate the observed E.M.F.'s in the ideal case of a transmitter situated on the surface of the earth and sending signals to a receiver at any other point, (*a*) when there is assumed to be no reflecting layer, and (*b*) when there is assumed to be a well-defined reflecting layer.

The comparison of the observed results with these formulæ will give information regarding the nature of the transmission, for it will be shown that the values derived from (*a*) fall short of the observed results, and we must therefore abandon the hypothesis that the waves travel round the earth without the aid of a reflecting layer, and compare the results with the formula (*b*) to see how nearly the assumption of a well-defined reflecting layer is justified.

The formulæ in question are :—

(*a*) *Diffraction formula.**

$$E \text{ (in volts per metre)} = \frac{0\cdot5365 I h e^{-23\cdot9\theta/\lambda^{\frac{1}{3}}}}{\lambda^{\frac{7}{6}} (\sin\theta)^{\frac{1}{2}}}$$

where h = effective height of the transmitter (in km),
λ = wave-length (in km),
I = transmitting current,
θ = zenith angle between transmitter and receiver.

(*b*) *Reflection formula.*—The absolute value of this is not given by G. N. Watson, but he shows that the E.M.F consists of terms of the form

$$\frac{AhIe^{-\alpha d/\sqrt{\lambda}}}{\lambda(R\sin\theta)^{\frac{1}{2}}}$$

where d is the distance ($R\theta$) and the other quantities are as given in the previous formula, and

$$\alpha = \frac{1}{2H}\left\{\left(\frac{\mu_1\rho_1}{2c}\right)^{\frac{1}{2}} + \left(\frac{\mu_2\rho_2}{2c}\right)^{\frac{1}{2}}\right\}$$

ρ_1 = resistivity of the upper layer,
ρ_2 = resistivity of the earth,
H = height of layer above the earth,
c = velocity of light,
μ_1 = permeability of upper medium, and
μ_2 = permeability of earth.

* VAN DER POL: *Philosophical Magazine*.

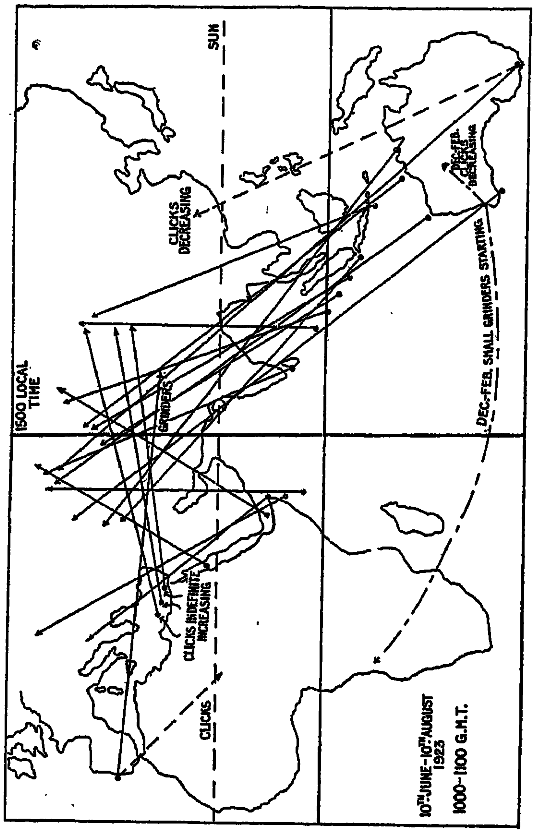


FIG. 82.

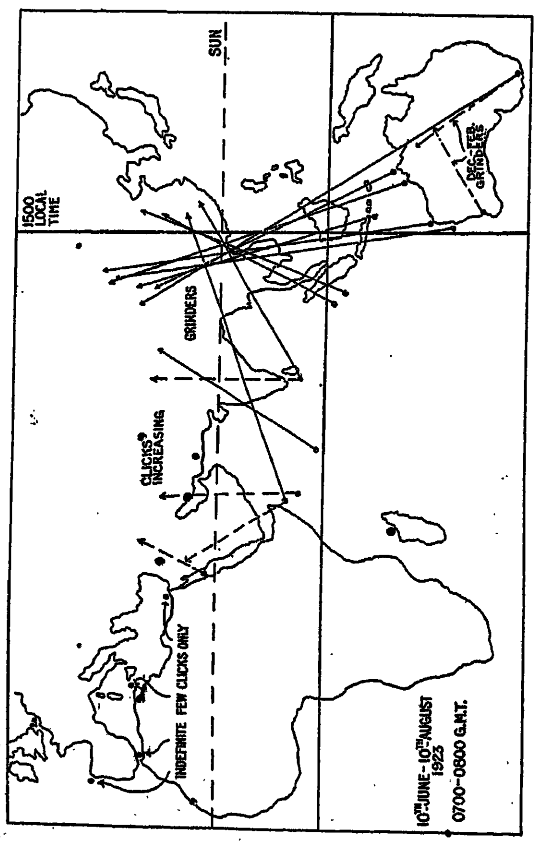


FIG. 81.

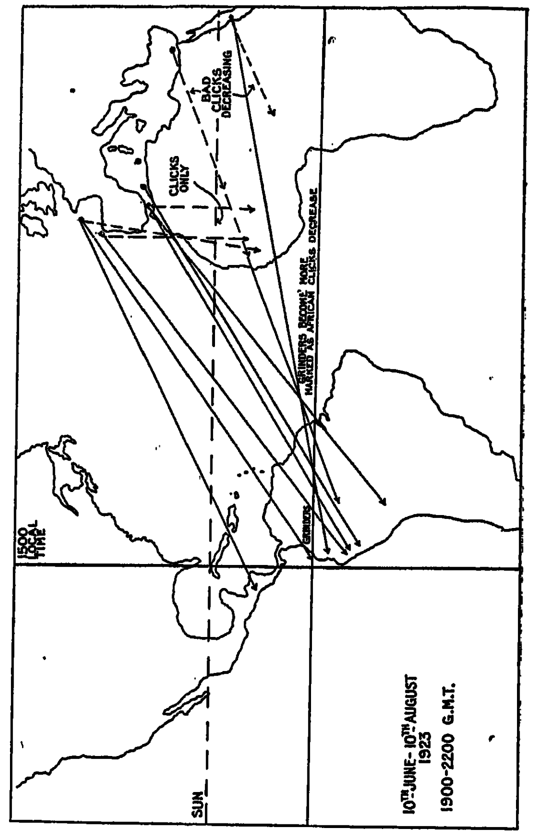


FIG. 84

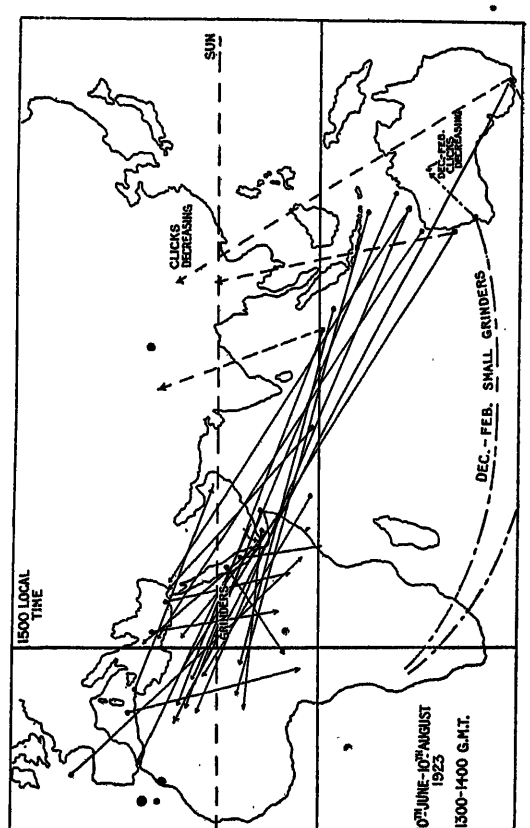
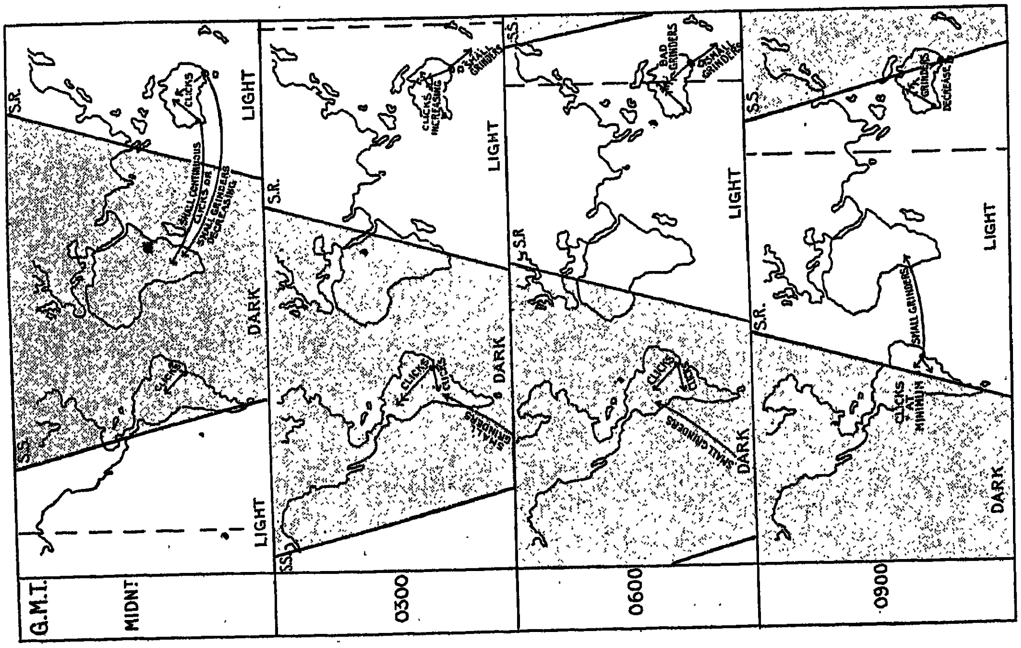
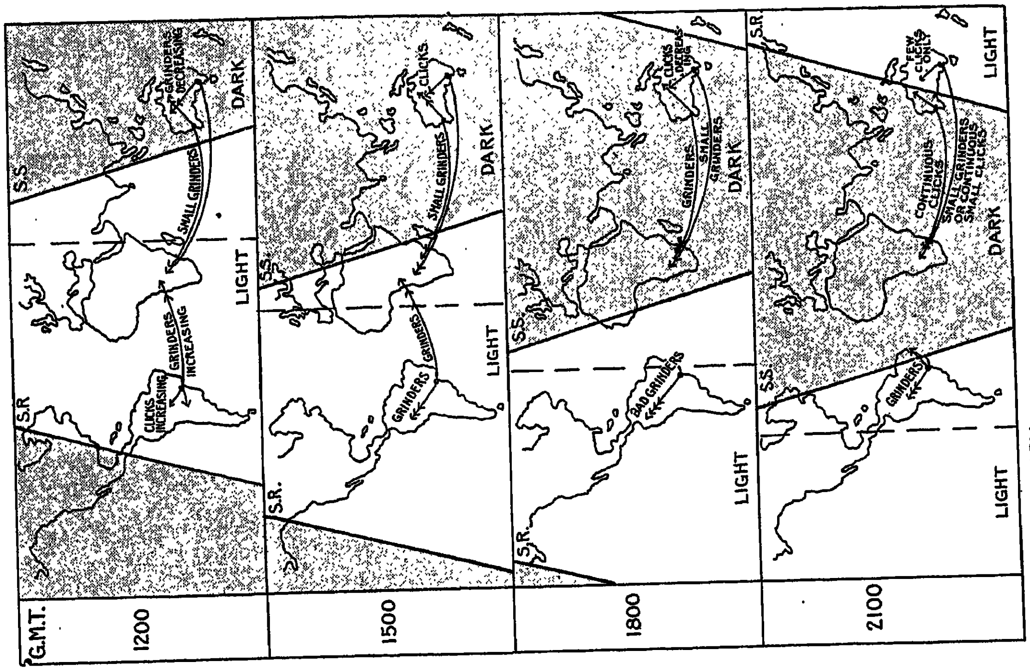


FIG. 83.



FEBRUARY
DOTTED LINE = 3 P.M. LOCAL TIME
ARROWS DENOTE APPROXIMATE INTENSITY
→→→ VERY BAD
——→ VERY GOOD

FIG. 85.



FEBRUARY
DOTTED LINE = 3 P.M. LOCAL TIME
ARROWS DENOTE APPROXIMATE INTENSITY
→→→ VERY BAD
——→ VERY GOOD

FIG. 86.

Comparison with diffraction formula.—The theoretical values derived from (*a*), the diffraction formula, are on some of the curves in Figs. 17 to 30, as well as the actual values obtained on the S.S. " Dorset " in the Atlantic.

The absolute values depend on the assumed values of the effective height and transmission currents of the sending stations. The values assumed are given in Table 10. In some cases the assumed values of the effective height may be open to a certain amount of doubt, but they are not likely to be more than 15 or 20 per cent in error. In any case this doubt does not affect the main result, that at distances greater than about 2 000 km diffraction alone is wholly inadequate to explain the observed results. At smaller distances, however, the observed and calculated curves are in better agreement, and at 300 or 400 km distance the observed values are only slightly in excess of the calculated ones.

These results, as before stated, drive us to the assumption of some form of reflecting layer. The effect of reflection, it would appear, begins to be important at distances of about 700 km, and at distances greater than about 2 000 km the effect of diffraction alone is wholly insignificant and Watson's second expression, i.e. the reflection formula, should be applicable.

Physical meaning of formula.—Before describing the results of this comparison, it would be well to make a digression and explain the physical meaning of Watson's second formula, given in (*b*) above.

The similarity between this and Austin's formula is very great. The exponential factor is of the same form, but the factor $AIh/[\lambda(R \sin \theta)^{\frac{1}{2}}]$ is different in respect of the denominator, which is proportional to $(\sin \theta)^{\frac{1}{2}}$ in Watson's formula.

The radiated energy, which is proportional to E^2, varies as $1/(R \sin \theta)$ in the Watson formula, and as $1/(R^2 \sin^2 \theta)$ in the Austin formula, where, since it varies inversely as the square of the distance, it represents a spherically expanding wave. In the former case the radiated energy, except for the exponential factor, varies inversely as $R \sin \theta$. This is the appropriate factor for the transmission of energy between two circular shells. The intersection of these by a cone of angle θ will form a ring of area $2\pi HR \sin \theta$ through which the energy must be radiated, and since the energy flow per unit area is $A/(R \sin \theta)$ the total flow through any two such rings, namely

$$\frac{A}{R \sin \theta} 2\pi HR \sin \theta$$

is constant, except for the loss represented by the exponential factor.

With regard to the attenuation factor, this, it will be observed, is of the same form as in Austin's formula, but the attenuation constant α in Watson's formula, instead of being an empirical constant, is a function of the resistivities of the two layers and the distance between them. The greater the resistivity of either, the greater is the attenuation. On the other hand, the greater the distance apart of the layers the less is the attenuation. This is because the energy is not frittered away so quickly when the distance between the layers is large, so that there is more energy to draw from.

It is interesting to note that a plane, or approximately plane, wave travelling between two flat surfaces which are the same distance H apart, and of the same resistivities ρ_1 and ρ_2, suffers the same attenuation as the above.* It follows that the slight curvature of the earth's surface has no perceptible effect upon the attenuation; the bounding walls merely act as guides and take their quota of energy independently of their curvature.

To sum up, Watson's formula expresses the fact that the energy is guided between the inner and outer sphere and is attenuated on account of the loss in the bounding walls, this attenuation to the first approximation at least being independent of the curvature of the surfaces.

To put the expression in a form suitable for calculation, we have assumed that E can be expressed in the form

$$E = \frac{120\pi hIe^{-\alpha d/\lambda^{\frac{1}{2}}}}{\lambda(d_0 R \sin \theta)^{\frac{1}{2}}}$$

in which the interference due to the several terms in Watson's expression has been neglected, for reasons

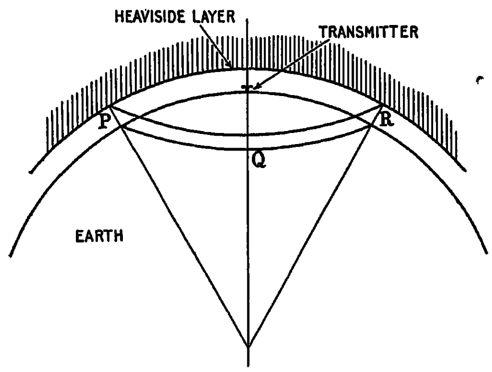


FIG. 87.

to be given later, and in which the semi-empirical distance d_0 has been introduced. The quantity d_0 must be of the dimensions of a distance to fit in with the other dimensions of the formula. If all the energy emitted is assumed to be radiated uniformly through any annulus PQR (see Fig. 87) the distance d_0 will be $3H/2$, where H is the height of the layer.

For the energy radiated is

$$\frac{40(2\pi)^2 h^2 (I_{\text{r.m.s.}})^2}{2\lambda^2}$$

Also the energy radiated through the annulus is $\frac{E^2}{4\pi c}$ ergs per unit area, or $\frac{E^{2} 10^{-7}}{4\pi c}$ watts. The area of the annulus is $2\pi HR \sin \theta$, i.e. the energy radiated through the annulus is

$$\frac{E^2 \times 10^{-7} R \sin \theta}{2c}$$

* The extension of a piece of analysis by J. J. THOMSON in " Recent Researches in Electricity and Magnetism."

Equating the two we get:

$$E = \frac{120\pi h I}{\lambda[(3/2)HR \sin \theta]^{\frac{1}{2}}}$$

and $d_0 = 3H/2$, neglecting the absorption factor.

The value of d_0 so obtained is obviously too small, since it assumes that the whole of the energy arrives at OPQ, and it is probable that the energy radiated almost vertically near the transmitter will escape or be lost in the semi-conducting layer.

Comparison of the Observed Results with Formula.

The procedure is as follows: The value of E, the signal strength in microvolts per metre, for every 500 km is taken from the smooth curve, and the logarithm of this is added to the logarithm of $(R \sin \theta)^{\frac{1}{2}}$ for this distance. If E is of the form

$$E = \frac{120\pi I h e^{-\alpha d/\lambda^{\frac{1}{2}}}}{\lambda(d_0 R \sin \theta)^{\frac{1}{2}}}$$

then $\log (R \sin \theta)^{\frac{1}{2}} + \log E = \log \left(\frac{120\pi h I}{\lambda (d_0)^{\frac{1}{2}}}\right) + \frac{-\alpha d}{\lambda^{\frac{1}{2}}}$.

This quantity plotted as a function of d should be a straight line, the slope of which is $-\alpha/\lambda^{\frac{1}{2}}$. The value of λ being known, it is possible to determine the value of α.

The results at great distances are complicated by transmission both ways round the world, as described in the earlier portion of this paper, but this effect should not be appreciable at distances less than about 12 000 km. We may take 10 000 km, or one-quarter of the circumference of the world, as a safe limit.

It will be obvious from even a casual glance at the attenuation curves obtained on the voyages of the S.S. "Dorset" and "Boonah" that the attenuation varies from place to place and may even vary with the direction of transmission. In view of this the instantaneous value of α, i.e. the slope of the curve, should be plotted as a function of the distance for all distances.

Owing to the variability of the data, however, the mean values of the slope for distances less than about 2 000 km are very ill determined, so that it is necessary to take the mean value of the slope over at least 4 000 or 5 000 km before a reliable determination of α can be made. Another source of confusion is the fact that the total attenuation may not be a function of the distance alone but may vary with the direction of the ray. For instance, if the course of the ship is inclined at an angle to the great circle joining the ship and the transmitting station under consideration, the change of signal strength with distance does not necessarily give the "instantaneous value" of α but also includes the change of the "mean value" of α with the direction of the ray. In view of these considerations the observations on the voyage of the S.S. "Dorset" have been divided into three parts, in each of which the values of α appear to be sufficiently constant to determine it fairly accurately. The first group comprises those observations taken on the Atlantic voyage, i.e. from Liverpool to Newport News; the second those on the voyage between Newport News and Panama, and the third those between Panama and New Zealand, but excluding those that were taken at distances greater than about 12 000 km from the transmitter. During the Atlantic voyage the course of the ship followed approximately the direction of the great circles from the transmitting stations, so that the results should not be complicated with the variations caused by changing ray directions. At the same time the rays were practically wholly over sea, and the effect of land absorption should be practically absent.

The actual mean values of α have been determined for the 10 stations given in Table 7.

TABLE 7.

European Stations.

Station	λ	α
	km	
Bordeaux (LY)	23·45	0·00223
Hanover (OUI)	14·7	0·00193
Carnarvon (MUU)	14·1	0·00183
Nauen (POZ)	12·6	0·00144
Stavanger (LCM)	12·0	0·00181
Rome (IDO)	11·0	0·00158
Clifden (MFT)	5·8	0·00193

Mean $= 0{\cdot}001802 \pm 0{\cdot}000112$
$= (1{\cdot}8 \pm 0{\cdot}112) \times 10^{-3}$

American Stations.

Station	λ	α
	km	
Rocky Point (WQK) ..	16·45	0·00135
Tuckerton (WGG)	16·0	0·00133
New Brunswick (WII) ..	13·6	0·00153
Marion (WSO)	11·5	0·00148

Mean $= 0{\cdot}00142 \pm 0{\cdot}000033$

The European and the American stations have been grouped separately because there appears to be a real difference in the mean values of α for the two groups. This difference, 0·00038 (0·00180 − 0·00142), is more than three times the probable error of either group and can therefore be considered to be a real and not an accidental difference due to the uncertainty of the readings.

Apart from this difference, which comes as rather a shock to our preconceived notions of reversibility in optics, and which will be discussed in greater detail later, the value of α is practically independent of the wave-length.

In the curves (Fig. 88) α is plotted against wave-length; except for LY on a 23·45 km wave-length, which has an excessively high value of absorption, the values are very approximately constant.

For transmission across the Atlantic the observed values are in good agreement with a formula of the type

$$\frac{Ae^{-\alpha d/\sqrt{\lambda}}}{\lambda(R \sin \theta)^{\frac{1}{2}}}$$

i.e. a formula of the reflection type; and we may therefore conclude with a fair degree of certainty that transmission takes place in the space between the earth and an upper conducting layer.

The voyage from Newport News to Panama being only about 3 700 km affords no very well-determined ment above must be taken with a certain amount of reserve.

The European stations also show no very marked change of α for this portion of the voyage. The results are included therefore with the previous transatlantic values, and the figures given above refer to the mean

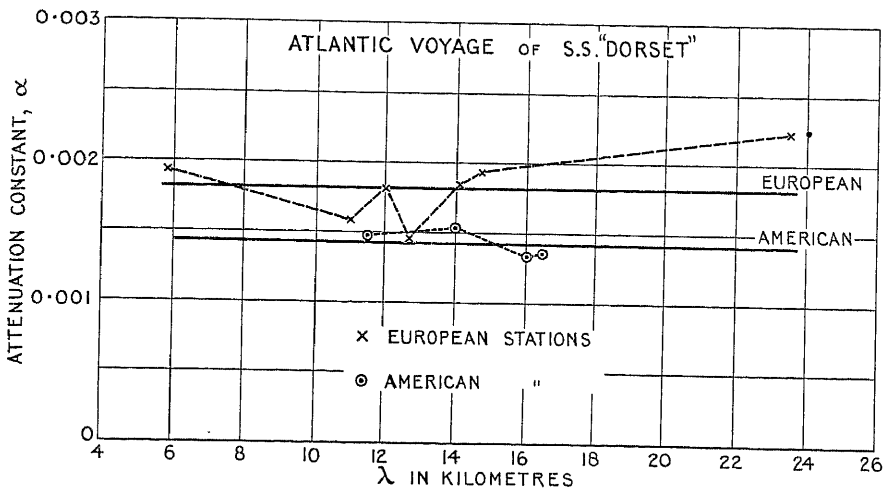


FIG. 88.

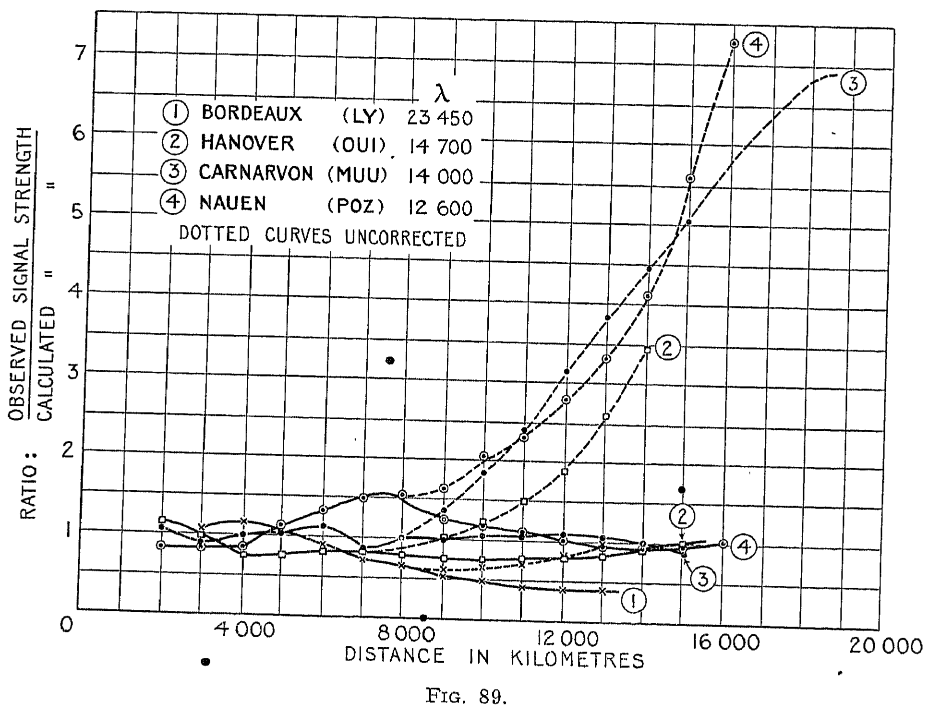


FIG. 89.

values of α. The direction of transmission from the American stations is nearly due South and the points obtained lie close to the curve already obtained for transatlantic transmission. Transmission southwards from the neighbourhood of New York is therefore practically the same as West to East transmission. The distance, however, is hardly sufficient to disclose any small changes in attenuation, so that the state-value for the whole voyage to Panama. The change of angle of the ray from the European stations is only of the order of a few degrees and has therefore little effect on the attenuation.

TRANSMISSION IN THE PACIFIC.

European stations.—The ray from Carnarvon during the voyage between Panama (7 700 km) and Pitcairn

Island (14 000 km) in the Pacific crosses only an insignificant amount of land in the region of the narrow part of Mexico. In direction also the ray remains within the limits traced out by the great circles to New York and to Panama respectively, which include an angle of approximately 10°. This is also approximately true of the other European stations, so that the determinations of attenuation of the European signals for this path should not be complicated to any great extent by the effects of land absorption or variations in the direction of the ray.

On the other hand, the rays from the American stations vary considerably in direction as well as in the amount of land over which they pass. The two groups of stations will therefore be considered separately as before. Unfortunately Stavanger, Rome and Clifden, the shorter-wave stations, dropped out of the observations soon after Panama, the signals being too weak on account of the cumulative effect of absorption on these short waves. Bordeaux, Hanover, Carnarvon and Nauen were the only European ones remaining.

The attenuation constants determined in the manner previously described are given in Table 8.

TABLE 8.

Attenuation in the Pacific.

Station	Wave-length	α	Distance
	km		km
Bordeaux (LY) ..	23·45	0·001243	11 000
Hanover (OUI) ..	14·7	0·000822	11 000
Carnarvon (MUU)	14·1	0·000868	15 000
Nauen (POZ) ..	12·6	0·000890	16 000

Mean value = 0·000955.

The values of α so determined are practically only half those calculated for the transatlantic voyage, a result which is certainly very surprising.

These results are reflected in Fig. 89, in which the ratio of the observed results to those calculated from the formula

$$\frac{120\pi e^{-\alpha d/\lambda}}{\lambda(d_0 R \sin\theta)^{\frac{1}{2}}}$$

(in which α is assumed to be 0·0016) is plotted against distance. Up to a distance of about 8 000 km the agreement is very fairly good, but beyond this the observed values rapidly increase, and at distances of about 15 500 km the observed values may be as much as five or six times the calculated values. If, however, we assume an abrupt change in the attenuation constant at Panama the calculated results for the voyage beyond this will all be much greater, and the curves show that a very fair agreement is obtained if we assume that α is 0·00095 in this region (Fig. 90).

As mentioned before, long-distance transmission takes place in both directions round the world and no doubt part of the relative increase of signals is due to signals coming the other way round the world, but as will be seen later this effect is not sufficient to explain entirely the relatively large signals obtained, and we are driven to the assumption that there is an actual decrease of attenuation in the middle latitudes of the Pacific.

In confirmation of this we may consider the attenuation curves of Darien (NBA) and Cavite (NPO). NBA has rather a short wave (10 000 m) and a high initial absorption, but it steadies after 4 000 km and is nearly constant between 4 000 and 10 000 km, with an attenuation value equal to 0·00115. If we include this first 4 000 km the mean attenuation constant is 0·00138. Whichever value we take, it is considerably smaller than the value 0·00180 for transmission in the Atlantic.

Cavite (NPO) was only measured between 9 000 and 12 000 km and the attenuation constant is not very well determined. It lies between the limits 0·00065 and 0·00082, and certainly upholds the view that the attenuation is small in these regions.

Honolulu (KGI) shows a variation of attenuation with the direction of the ray, signals transmitted in a

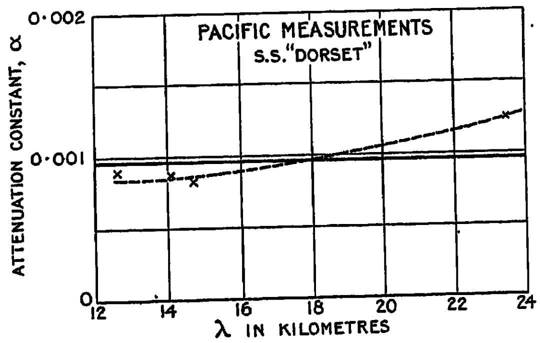


FIG. 90.

South-Easterly direction being stronger than those transmitted to the same distance in a Southerly or South-Westerly direction. The mean attenuation in the South-Easterly direction is 0·00128, but the range is short; in the South-Westerly direction the range is still shorter and no very definite value of α can be obtained.

New York stations.—The transmission of signals from the New York stations in the Pacific is complicated by the effects of varying land absorption and varying ray direction, but they all undoubtedly show a low value of attenuation in the Pacific, i.e. about 0·00114.

RETURN VOYAGE OF S.S. "BOONAH."

The signal strength curves have been shown in Figs. 60 to 70, and these can be treated in the same manner as the observations taken on the S.S. "Dorset," and the attenuation constants determined. In connection with the results of this determination certain broad facts may be noted. In the first place, the measured values of the signal E.M.F.'s of the European stations at great distances, say about 10 000 km or more, greatly exceed those measured on the S.S. "Dorset" at the same distance, in spite of the fact that much of the transmission in the case of the S.S. "Boonah" was overland. At short distances from the transmitting stations the measured values in microvolts per metre agree fairly closely, so that the attenua-

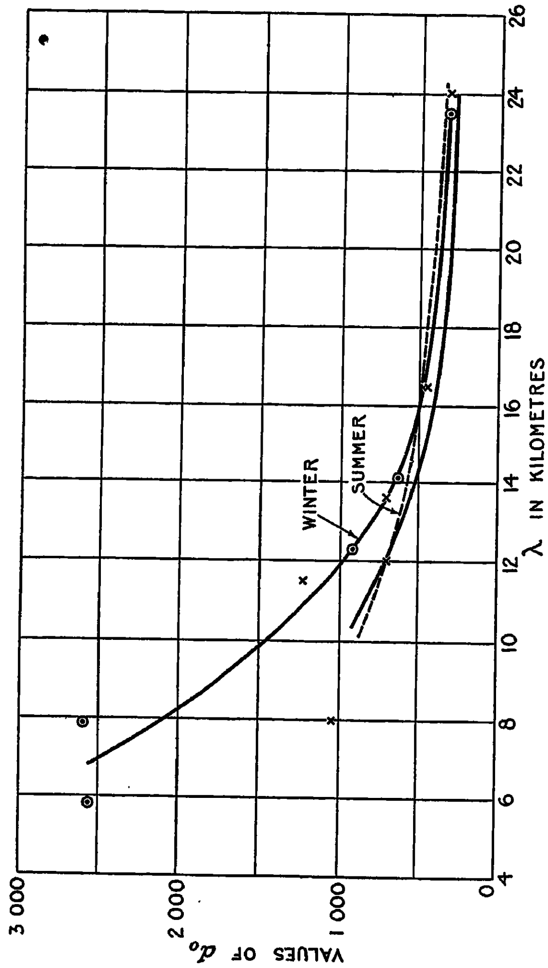


FIG. 92.

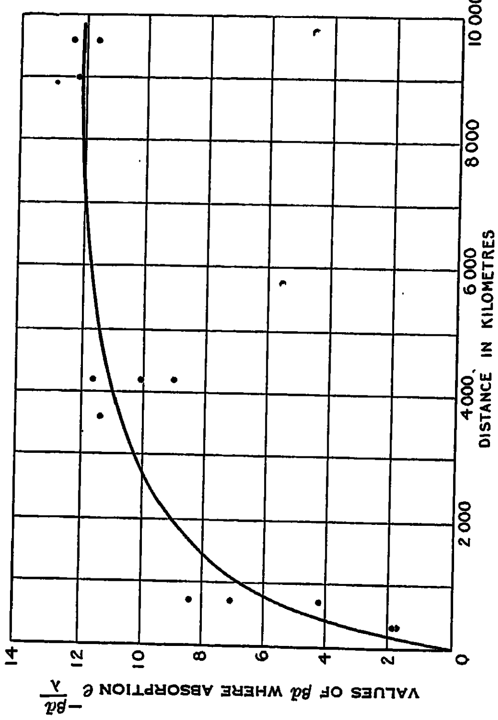


FIG. 94.

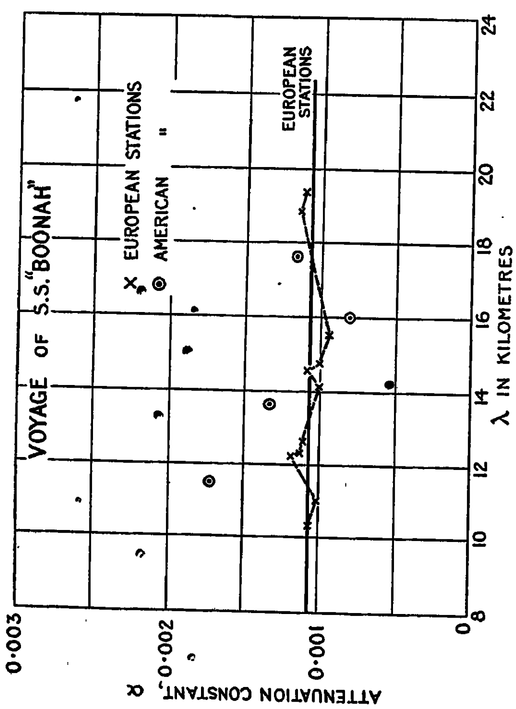


FIG. 91.

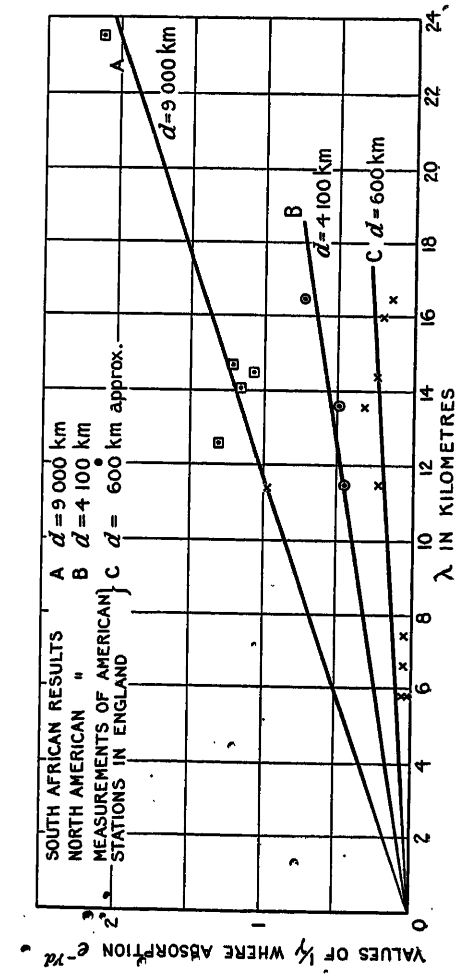


FIG. 93.

tion suffered by the signals travelling West to East during the voyage of the S.S. "Boonah" must be very considerably less than that experienced on the S.S. "Dorset" trip. The voyage of the S.S. "Dorset" took place during January, February and March, and the return voyage on the S.S. "Boonah" during June, July and August, so that the effect may be a seasonal one; but we are inclined to think this unlikely because the measured signals in Australia show no seasonal variation, and transmission of signals in the West to East direction received in Australia both from Europe and America is better than that in the opposite direction at all times. This is possibly an example of East and West effect, as it may be called, a further example of which is given in the case of the transatlantic signals, for which the attenuation constant for West to East transmission is considerably less than that found for East to West transmission.

In confirmation of this East and West effect we may cite the case of the signals from NPO, which are charted in Fig. 76. This figure shows the signals received on the S.S. "Dorset" in the Pacific, to the East of the station, and also the signals received on the S.S. "Boonah" during the return voyage, to the West of the station. It is obvious, even from a casual glance, that the latter are much more attenuated than the former, the values of the attenuation constants being 0·00190 for East to West transmission and about 0·00071 for transmission in the opposite direction.

The observations taken on the S.S. "Boonah" are complicated by land absorption, but neglecting this for the present we may determine the overall absorption coefficients between the limits of 2 000 and 10 000 km. These are given in Table 9. The instantaneous values of α, as well as the mean values of α for each station, show a remarkable constancy, and in view of the fact that the amount of land traversed by the rays varies very considerably both with the position of the transmitting station and with the ship's position, we are justified in assuming that variations in overland absorption are not very marked at distances greater than about 2 000 km. These attenuation constants are shown in Fig. 91.

The attenuation factors for signals transmitted from the American stations appear to be more variable and to increase with an increase in the frequency. The determination of the attenuation suffers very markedly from the fact that the ray direction from the S.S. "Boonah" varies rapidly with the position of the ship, and when the latter is about 14 000 km from New York the rays pass over the North and South Poles and no signals at all are received from these stations. This effect will be discussed more fully when considering long-distance transmission.

This completes the discussion on attenuation up to the relatively short distances of 10 000 km or so. The results are a little difficult to summarize, since they obviously indicate that the attenuation constant varies with the position of the ray on the earth's surface, probably even with the direction of transmission of the ray, and possibly with the season. The results obtained on the two voyages, and those obtained in South Africa and South America, are hardly sufficient to chart the world in respect of the value of the attenuation constant. We think, however, that it may be safely assumed that the transmission formula $\frac{AhIe^{-\alpha d/\lambda^{\frac{1}{2}}}}{\lambda(R\sin\theta)^{\frac{1}{2}}}$ is a fairly good approximation for over-sea transmission, and that the value of α is approximately independent of the wave-length, but depends on the locality and direction of the ray.

It was definitely proved that it was not possible to account for the observations by the effect of diffraction alone, and the Heaviside layer theory was therefore invoked. The observations are in good agreement with this theory if we assume that the nature of the layer, i.e. height, conductivity, or gradient of conductivity, varies from place to place on the earth's surface.

TABLE 9.

Station	Wave-length	α
	km	
UFU	19·3	0·00111
LY	18·8	0·00114
YN	15·5	0·00091
OUI	14·7	0·00101
UFT	14·5	0·00109
MUU	14·1	0·00100
POZ	12·6	0·00111
GBL	12·3	0·00113
LCM	12·2	0·00118
SUC	11·0	0·00101
UFZ	10·3	0·00106 ?

Mean = 0·00107

American Stations.

Station	Wave-length	α
	km	
WQL	17·6	0·00116
WGG	16·0	0·00075
WII	13·6	0·00133
WSO	11·5	0·00172

Mean = 0·00124

Absolute values of formula.—So far we have only discussed the form of the transmission formula in relation to the observed results. The absolute value depends, as we have seen, on the arbitrary distance d_0 in the expression

$$E \text{ (in volts per metre)} = \frac{120\pi Ihe^{-\alpha d/\lambda^{\frac{1}{2}}}}{\lambda(d_0 R\sin\theta)^{\frac{1}{2}}}$$

where d_0 is some function of the height and conductivity of the layer, and possibly of the wave-length. We may obtain the values of d_0 necessary to adjust the formula to give correct mean results when we know the values of transmitting current, effective height of transmitter, wave-length and d.

In the case of the observations made on the S.S. "Dorset" we have, by the courtesy of Mr. Alexanderson

of the Radio Corporation of America, the logs of the transmitting currents of the stations WQK, WGG, WII, and WSO, as well as the Pacific stations KET and KGI.

Signals from Carnarvon (MUU) were made at specified times during the outward voyage, and the transmitting currents were noted.

TABLE 10.

Values of d_0.

Station	Corrected mean transmitted current	Wave-length	Effective height	d_0
	A	km	m	km
WQK ..	600	16·45	90	451
WGG ..	—	16·0	67	—
WII ..	550	13·1	67	725
WSO ..	580	11·5	60	1 240
LY ..	490	23·45	150	337
MUU ..	300	14·1	75	635
LCM ..	260	12·3	75	910
GB ..	150	7·85	40	2 600
MFT ..	150	5·8	50	2 560

The values of d_0 given in the table are obtained in the following manner. We have

$$d_0^{\frac{1}{2}} = \frac{E(\text{obs.})(R \sin \theta e^{ad/\lambda^{\frac{1}{2}}})^{\frac{1}{2}}}{hI}$$

All the values on the right-hand side are known. d_0 is calculated for every 1 000 km and the mean value taken. The value of α is the mean of the trans-atlantic determinations. The values of d_0 are plotted as a function of λ in Fig. 92.

The values of d_0 obtained on the home voyage are complicated by land absorption, but allowing for this, in a way specified later, the results in Table 11 are obtained.

TABLE 11.

Values of d_0.

Station	Wave-length	h	I	d_0
	km	m	A	km
UFU ..	19·3	150	600	310
LY ..	18·8	150	500	350
OUI ..	14·7	—	—	446
UFT ..	14·5	150	600	425
MUU ..	14·1	75	300	580
POZ ..	12·6	140 ?	350 ?	400 ?
LCM ..	12·2	75	260	660

The values obtained all lie slightly below the previous ones, but in both cases the points lie fairly well on a smooth curve (Fig. 92).

The measurements made during 1921 in England of the signals from the American stations WGG, WII and WSO are interesting in this connection. These measurements were made before the Australian Expedition was projected, and therefore before any attenuation curves had been taken. Even then, in the absence of any experiments, we were inclined to favour, on theoretical grounds, a transmission formula of the Watson type, and the results obtained were accordingly used to determine the values of α and d_0 in the formula, assuming a constant value of d_0 for all wave-lengths between 11·5 and 16 km. The mean results obtained during the summer months were $\alpha = 0{\cdot}0016$ and $d_0 = 350$ km, and Table 12 gives the ratio of observed to calculated results.

With these values of α, d_0, and $\beta = 0{\cdot}005$ the ratios of observed to calculated values are given in Table 12.

β = land absorption coefficient (see later).

TABLE 12.

(*At Broomfield.*) (*Ratio of observed/calculated.*)

Station	Wave-length	Test number 1	2	3	4
	km				
Glace Bay ..	7·8	—	—	0·883	0·863
Marion	11·5	1·022	0·953	0·782	0·910
New Brunswick ..	13·6	1·098	1·155	1·564	1·640
Tuckerton ..	16·0	0·932	1·02	1·098	0·915
Rocky Point ..	16·45	—	—	—	1·305
Mean =		1·017	1·043	1·082	1·126

Station	Wave-length	Test number and place of test (2) Girvan	(3) Towyn	(4) Poldhu
	km			
Glace Bay ..	7·8	—	0·827	1·16
Marion	11·5	0·56	0·582	0·707
New Brunswick	13·6	0·976	1·076	1·015
Tuckerton ..	16·0	0·974	0·983	1·014
Rocky Point ..	16·45	—	—	1·030
Mean =		0·835	0·866	0·985

Test No. 1 at Broomfield, near Chelmsford, May 5 to 24, 1921.
Test No. 2 at Broomfield and Girvan, July 5 to 10.
Test No. 3 at Broomfield and Towyn, Aug. 31 to Sept. 9.
Test No. 4 at Broomfield and Poldhu, Oct. 10 to 19.

These results refer to the ratio of the mean observed result to the mean calculated result throughout each test. (Day values alone are included.) In view of the later confirmation of these values on the expedition of the S.S. "Dorset," the results are remarkable. The assumption of a constant value of d_0 is inclined to increase the apparent value of α, so that the summer value of α may be either equal to or less than the winter values.

In the light of the measurements made on the S.S. "Dorset" and S.S. "Boonah," which show that d_0 varies approximately as $1/\lambda$, the American summer

results, obtained at Girvan and Poldhu, where they are not complicated by land absorption, have been re-analysed on the assumption that $d_0 \propto 1/\lambda$, and the oversea absorption has been obtained. The results of these deductions are $\alpha = 0\cdot00138$ and $d_0 = 9\,400/\lambda$ approximately, in which case the ratio of observed to calculated signal strength is given in Table 13.

TABLE 13.

Ratio of observed/calculated.

Station	Wave-length	Girvan	Poldhu
	km		
Marion	11·5	0·764	0·878
New Brunswick ..	13·6	1·025	1·160
Tuckerton	16·15	1·973	1·004
Rocky Point	16·45	—	1·000
Mean =		0·921	1·01

The agreement is rather better than on the previous theory, and the value of α, i.e. 0·00138 for summer transmission, is slightly less than that for winter transmission, $\alpha = 0\cdot00144$.

These measurements on the American stations were continued practically throughout the year and it was discovered that there was a very marked annual variation, which is shown in Fig. 14. At the end of October or beginning of November there is a very marked drop of signal strength, which persists practically throughout the winter. This drop in signal strength in the winter months may be due either to a slight increase in the attenuation in these months or to an increase in d_0, or it may be due to both. In view of the evidence that the value of d_0 is greater in winter than in summer (see Fig. 92) this latter effect is certainly present, but the magnitude of the change is not sufficient to account for the whole difference between the winter and summer results. We think, therefore, that there is some slight change in attenuation as well.

LAND ABSORPTION.

The separation of the land absorption from the atmospheric absorption is a matter of considerable difficulty. If the value of the over-sea or atmospheric attenuation had been sufficiently constant, i.e. the same for all points on the surface of the earth for all directions of the ray, etc., it would have been a matter of little difficulty to calculate what the signal strength should be if there were no land absorption, and compare it with the actual result and attribute the difference to overland absorption. For in general where the ray passes over a considerable amount of land the signal strength is weaker than that calculated on the assumption that "atmospheric absorption" alone is present. The difference is due to the energy lost in transit over the land. Since, however, the atmospheric absorption varies from place to place, it is difficult to know when comparing transmission over sea with that over land how much of the difference to attribute to over-land absorption and how much to local differences of atmospheric absorption.

The comparison therefore entails a certain amount of guesswork in fixing the probable amount of atmospheric absorption, and the determination of the land absorption is open to a certain amount of doubt. A general survey of all the results obtained up to date will help to point out the main effects of the presence of land. In the first place, measurements in South Africa show that, metre-ampere for metre-ampere, the signal strengths of the European stations are about 50 per cent of the signal strengths of the American stations. The rays from the European stations are practically wholly over land, whereas transmission between New York and South Africa is practically wholly over sea.

The difference is probably not entirely due to over-land absorption, for the direction of the New York–South African great circle is slightly more favourable for transmission than the Europe–South Africa great circle. The latter is practically due South and the former is at least partly from W to E, a direction which we have found favours transmission. Assuming, however, that the atmospheric absorption is the same in both cases, we get what is probably a slight over-estimate of the over-land absorption for the Europe–South Africa route.

The average overall attenuation constant for the American stations WQL, WQK, WII, and WSO on the transmission route to South Africa is 0·00113, and is very well determined. Using this value of α for the European stations we get the values of the ratio of observed to calculated signals shown in Table 14.

TABLE 14.

Station	Ratio	$\beta d/\lambda$	d(land)
			km
Hanover (OUI) ..	0·450	0·800	9 100
St. Assise (UFT) ..	0·430	0·845	9 000
Carnarvon (MUU) ..	0·436	0·830	9 600
Nauen (POZ) ..	0·508	0·677	9 100

The atmospheric absorption of Bordeaux (LY) on a 23·45 km wave being abnormally high, it is not included, but the signals are abnormally low, suggesting as before a large atmospheric absorption.

If we assume that the land attenuation is of the form $e^{-\beta d/\lambda}$ the values of β are:

	β
Hanover	0·00129
St. Assise	0·00136
Carnarvon	0·00121
Nauen	0·00129
Mean	0·00129

It will be noted that β is fairly constant.

SHORT-DISTANCE LAND ABSORPTION.

Another set of fairly unequivocal determinations of the land absorption can be obtained from measurements of the American stations in England during 1921. A

fairly accurate estimate of the atmospheric absorption has been made in transatlantic transmission. If allowance is made for this in comparing the simultaneous results obtained at Girvan and Chelmsford, the absorption of the ray when travelling over the 600 km of land included in the path from New York to Chelmsford can be calculated.

The curves shown in Fig. 93 are compiled from the data just cited. The value of $1/\gamma$ is plotted against λ, where the absorption factor is assumed to be of the form $e^{-\gamma d}$. This method is adopted since preliminary measurements suggest that $\gamma \propto 1/\lambda$ nearly, or $1/\gamma \propto \lambda$. The results at first sight appear to be meagre, but it must be remembered that, in general, each point represents a large number of observations.

It is fairly obvious from Fig. 93 that γ is a function of d, the distance travelled over land, as well as of λ, the wave-length. It will be observed that at distances greater than about 3 000 km γd is constant; this is shown in the curves of γd plotted against distance (Fig. 94). For small values of d, γd is proportional to d, but as d increases the quantity γd tends to a limit. The practical significance of this is very remarkable and is of considerable importance. Since the ratio of the actual signal strength for the over-land path to the strength which would be obtained if the path were over sea, is $e^{-\gamma d}$, the results show that the effect of land absorption tends to a limit after a distance of about 3 000 km is reached. Thus, however far the ray travels over land, beyond a distance of 3 000 km the effect of the land is only to produce a limited reduction in strength, which is about 50 per cent for wave-lengths in the neighbourhood of 15 km. The range of wave-lengths to which this law applies with any certainty is, say, 10 to 25 km.

The material is hardly sufficient to determine the exact law of variation of γ with wave-length, the range of wave-lengths being too small, but it may be conjectured that $1/\gamma$ increases with λ, possibly at some rate between the first and second power, since the observations on short wave-lengths suggest that the increase is more than linear. It seems unlikely at any rate that $1/\gamma$ varies as $\lambda^{\frac{1}{2}}$, as is the case with atmospheric absorption, so that the mechanism of over-land absorption is probably quite different.

THEORY.

Any theory which will account for all these effects is necessarily very complex, the nature of the absorption being different for long-distance and short-distance over-land transmission, as well as for long wave-lengths and short wave-lengths.

The waves in passing over the earth's surface produce currents in the earth and, on account of the resistivity of the earth's material, power must be supplied, which will result in attenuation of the signal. Other losses that may be present at the earth's surface, and which will cause absorption, are:

(1) Dielectric loss in the surface vegetation, and
(2) Conduction losses in the various structures on the surface, as well as the surface vegetation.

With regard to (1), experiments on the resistance of aerials have shown it to be present to quite an appreciable extent. The presence of trees, iron-frame buildings, etc., will no doubt produce a certain amount of loss. It is probable that all these factors are present in any actual case. The evidence, however, points to the fact that the conduction loss in the earth is negligible compared with the others at, say, more than a few hundred kilometres from the transmitter.

At these distances we can picture the wave as being approximately uniformly distributed in the space between the earth's surface and the upper conducting layer, and the nature of the transmission, as has been shown before, is practically the same as that between two conducting planes. The total attenuation can then be shown to be the sum of the attenuations due to the upper conductor and the lower one separately, being, in fact,

$$\frac{1}{2H}\left\{\left(\frac{\rho_1\mu_1}{2c\lambda}\right)^{\frac{1}{2}} + \left(\frac{\rho_2\mu_2}{2c\lambda}\right)^{\frac{1}{2}}\right\}$$

that is

$$\frac{\mu^{\frac{1}{2}}}{2H(2c\lambda)^{\frac{1}{2}}}\{\rho_1^{\frac{1}{2}} + \rho_2^{\frac{1}{2}}\}$$

where H = distance between the upper and lower conductors,
λ = wave-length,
ρ_1, ρ_2 = resistivities of the upper and lower conducting layers respectively, and
c = velocity of light.

The value of ρ_2, the resistivity of the earth, varies, of course, enormously from place to place, but measurements made in various parts of England show that as a rule it varies between 10^{12} and 10^{13} C.G.S. units.

The amount of contribution of the earth currents to the total attenuation, i.e. $(\mu_2\rho_2)^{\frac{1}{2}}/2H(2c\lambda)^{\frac{1}{2}}$, depends on the distance H between the earth's surface and the upper conducting layer, but we can easily put a lower limit to H from the known constants of the atmosphere, and a value of H = 10 km will be well below the least possible height of the layer.

Inserting these values in the above quantity, we find that anywhere within the wave-length range 6 000 to 24 000 m the attenuation due to this cause is absolutely negligible. In any case the actual attenuation varies as $1/\lambda^n$ where $n > 1$, and the attenuation due to earth currents varies as $1/\lambda^{\frac{1}{2}}$, so that in view of these two reasons this source of attenuation is probably negligible except, possibly, close to the transmitter.

SURFACE DIELECTRIC LOSS.

The attenuation caused by this surface loss can be shown to vary approximately as $1/\lambda$, as is required by the observed results; for consider the space between two surfaces S_1, S_2 (Fig. 95), perpendicular to the direction of propagation of the wave and to the bounding surfaces, and let us suppose as a first approximation that the electric force is uniformly distributed between the upper layer and the earth.

Then, by Poynting's theorem, the rate of supply of energy through the surface S_1 per unit depth is $\frac{c}{4\pi}(XHM)$

where X = electric force, and
M = magnetic force,

and, since $M = cX$,

$$P_1 = \frac{c^2H^2(X)^2}{4\pi}$$

and the power supplied through S_2 is

$$P_2 = \frac{c^2H^2(X_1)^2}{4\pi}$$

The difference in the powers supplied through the two surfaces is equal to the power wasted in dielectric

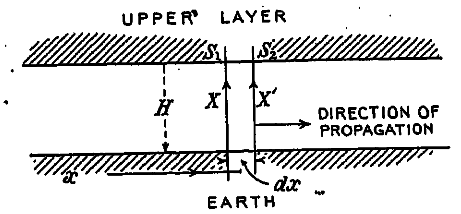


FIG. 95.—Showing land absorption.

loss, i.e. gnX^2dx, where g is a constant, n is the frequency and dx is the distance between the two surfaces. Thus

$$\frac{c^2}{4\pi}H(X^2 - X_1^2) = gnX^2dx$$

and

$$X_1^2 = X^2 - \frac{\partial X^2}{\partial x}dx$$

so that

$$-\frac{cH^2}{4\pi}\cdot\frac{\partial X^2}{\partial x} = gnX^2$$

or

$$X = X_0e^{-gn4\pi x/(2c^2H)}$$

The absorption coefficient is then

$$\frac{4\pi gn}{2c^2H} = \frac{2\pi g}{cH\lambda}$$

which, it will be observed, is inversely proportional to λ. It is also inversely proportional to H, as in the case of the resistive loss. This latter property appears to be a natural consequence of the assumption of a surface loss.

This theory offers a rough explanation of the variation of absorption with distance. For consider the state of affairs in the neighbourhood of the transmitter. The difference in power radiated from the two spheres S_1

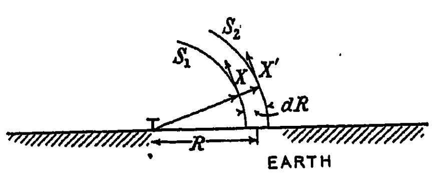


FIG. 96.

and S_2 (Fig. 96) surrounding the transmitter is approximately

$$-\frac{c^2}{4\pi}\cdot\frac{\partial X_0^2}{\partial x}\cdot 2\pi R^2\cdot\frac{2}{3}dx$$

where R is the radius of the spheres, supposed small compared with H, and the energy wasted is

$$2\pi RgnX^2dx$$

that is,

$$-\frac{c^2}{4\pi}\cdot\frac{2}{3}\cdot\frac{\partial X^2}{\partial x} = \frac{gnX^2dx}{R}$$

or

$$X = X_0e^{-4\pi gnx/(2c^2\frac{4}{3}R)}$$

Comparing this with the previous formula, we see that H is replaced by $4R/3$, so that for values of R small compared with H the absorption on this account is large compared with the absorption at a great distance where the wave has settled down to a uniform distribution between the upper and lower layer.

This theory is admittedly only very approximate, for in the first place the distribution of the electric and magnetic fields is assumed to be unaffected by the ground loss, and, secondly, the readjustment of these forces due to the surface absorption at P, say, is assumed to take place simultaneously throughout the space between the two surfaces S_1 and S_2. This can only be approximately the case when all the distances involved are small compared with λ. Nevertheless, further analysis confirms the main conclusions, viz. that on account of the surface loss the absorption factor decreases with the distance.

A more accurate method of attacking this problem is to consider the ray passing from transmitter to re-

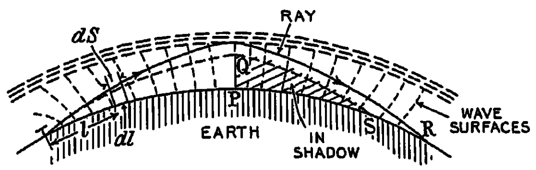


FIG. 97.

ceiver. Although as yet we have very little information as to the path of this ray, there can be little doubt that when transmission takes place over a long distance the ray passes at a considerable height over the earth's surface. Thus we can picture it as being somewhat of the form shown in Fig. 97.

The reflection at the upper surface is supposed to be continuous and gradual, more resembling refraction than reflection pure and simple. The wave surfaces, instead of being, as before assumed, perpendicular to the earth's surface are perpendicular to the ray and are slightly tilted, the state being only slightly different from that assumed previously.

Considering the ray from the point of view of pure optics, we know that if a screen is placed at PQ, say, the top edge of which is below the ray, and if the height of the ray above the surface of the earth is more than a few wave-lengths, then the screen will not impede the ray and the reception of energy at R will be practically unaltered. The region below QS will be in electrical shadow, to an extent depending on the dimensions of the screen PQ compared with the wave-length. When the screen is big enough there will be practically no electromagnetic forces at the earth's surface in the region beyond P. Consequently there can be no losses in the ground in this region; but since the screen makes practically no difference to the signal received, the contribution by ground loss to the attenuation

in the region beyond P must be negligible if the ray passes at a sufficient height. The validity of this argument rests on the assumption that the height of the ray should be more than a few wave-lengths above the surface, so that the region QS is in the shadow. To answer the question "How many wave-lengths?" requires a rather detailed mathematical discussion, the outlines of which are given here.

The energy loss is a local effect at the surface of the earth, and the effect of this energy loss on a ray at a given height can be calculated when the surface distribution of electric forces and currents is known. The total effect of this can be obtained by summing up the effects of these at a point P on the ray, due attention being paid to the fact that it takes a definite time, i.e. r/c, for the currents on the earth's surface to produce their effects at P, so that the distribution in time as well as in space must be known (see Fig. 98).

If the wave travels in a medium above the surface of the earth with the velocity of light, the time taken for a change at Q to produce its effect at P is r/c, where r is the distance from Q to P, and c is the velocity of light.

The fact, however, that the ray bends round with the curvature of the earth, as in Fig. 97, shows that the actual "phase velocity" of the wave increases with the height and so the actual time taken by the wave along the path is less than that taken along the

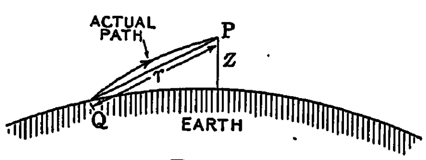


FIG. 98.

direct path QP (by Fermat's principle), which in its turn is also less than the time taken along QP in the free ether. It follows, therefore, that $T < r/c = kr/c$, say, where k is a quantity less than unity. If we assume that the distribution of current on the earth's surface is sinusoidal, the wave-length being practically the same as that in free space, we have sufficient data to calculate the disturbing effect of the surface loss on the ray at P, say, a height Z above the earth's surface.

Making these assumptions the following theoretical results were obtained, k being assumed to be 0·99, i.e. differing only by 1 per cent from unity. In Fig. 99 is shown the relative effect of land absorption on a ray at different heights. The ordinates represent the absorption on an arbitrary scale and the abscissæ the heights. The wave-length assumed is 20 km.

If k is a constant for all wave-lengths, then the ordinates are only a function of Z/λ, Z being a height above the earth's surface, so that the same curve applies for different wave-lengths if the horizontal scale is altered in proportion to λ. The curve obtained is very approximately exponential, so that the absorption for rays of different heights is expressible in the form $e^{-mZ/\lambda}$, where m in the case assumed is 1·06, Z and λ being in km with a wave-length of 15 km. The absorption at a height of 50 km is therefore $e^{-1\cdot 06 \times 50/15} = e^{-3\cdot 53} = 0\cdot 029$, say 0·03 of its surface value, i.e. is practically negligible.

On the assumption that the absorption decreases exponentially with the height, we can get an estimate of the relation between the total absorption and the distance between receiver and transmitter. The actual total absorption will be the sum of the absorption per unit length, i.e. $\int \beta_z dZ$, where β_z is the value of the absorption factor at height Z. Now $\beta_z = \beta_0 e^{-\gamma_1 Z}$, say, where β_0 is the value of the absorption when the ray is close to the surface, and Z is the height of the ray above the ground. Now ds, the element of length measured along the ray, is practically indistinguishable from dl, where dl is the projection of ds on the earth's surface (Fig. 98), so that the total absorption is approximately

$$X = \int \beta_0 e^{-\gamma z} dl$$

In order to make this determinate we must express Z as a function of l. On the simple assumption that the height Z of the ray is proportional to the distance travelled we get

$$X = 2\int_0^{d/2} \beta_0 e^{-\gamma (Z/d) l} dl$$

$$= 2\int_0^{d/2} e^{-\gamma P l} dl$$

where Z/l constant $= P$ say.

$$= \frac{2\beta_0}{\gamma P}(1 - e^{\gamma P d/2})$$

$$= \frac{\beta_0}{S}(1 - e^{-sd})$$

where $S = \gamma P/2$.

When sd is sufficiently small this is $\lambda = \beta_0 d$; but the total absorption X tends to the limit β_0/S as d increases. With regard to these two characteristics, this theoretical value agrees with the actual values, for the curve (Fig. 94) is very approximately of the form $A(1 - e^{-sd})$. The coefficient A in the actual curve is, however, not β_0/S but is approximately $2\beta_0/S$, so that the simple assumption that the height of the ray is proportional to the distance is not justified. The agreement is such, however, as to confirm the belief that the explanation given is approximately correct.

Summarizing the above, apart from theory, when we wish to take practical account of the effect of land absorption and calculate the reduction in signals effected by it we must proceed as follows: In the first place, where there is an unbroken stretch of land between the transmitter and receiver, these being a distance d apart, ascertain from the curve the value of βd corresponding to this distance, and divide this by λ, the transmitting wave-length. If the resulting quantity is x, then the effect of the land absorption is to reduce the signals in the ratio of e^{-x} to 1, roughly.*

This procedure obviously takes no account of variations in land absorption and can therefore be considered to be only a sort of average effect, but it apparently

* The values of the European station E.M.F. observed on the S.S. "Boonah" have been corrected with this factor in determining the values of d_0.

serves to give results with a fair degree of accuracy for wave-lengths ranging between 5 km and 25 km.

When the land does not stretch continuously between the transmitter the procedure is more complex, but working on the principle that land is only effective in the neighbourhood of the transmitter or receiver it is not difficult to get an estimate, by using Fig. 94, of the effect in any given case.

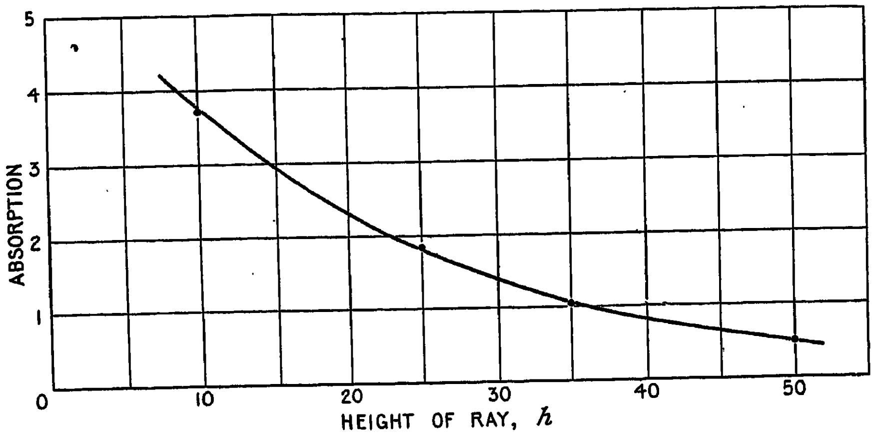


Fig. 99.

The effect of land absorption due to land close to the receiving station is shown clearly in Fig. 67, where the increase of signal strength on clearing the Indian peninsula is particularly marked.

Night Attenuation.

At great distances (when the short path is in daylight the longer path is practically wholly in darkness) the signals come round both ways and interfère. Signals may prefer to come round by the long path (the attenuation being less at night) even when this path is as much as two-thirds earth's circumference and the short path only one-third. The American signals are an example of this, for beats due to the bi-directional signals began to appear at a distance of only about 13 000 km West of New York.

In order to study these long-distance effects quantitatively we require a knowledge of the night attenuation. Unfortunately, only few night readings were taken, either on the voyage out or on the return voyage, since it was impossible to keep a 24-hour watch, but this want can be made good by some observations published by Lt. M. Guirre in *Radioélectricité*, March and May, 1921. The observations were taken on the French battleship " Aldebaran " during a voyage through the Mediterranean and the Suez Canal, and down the coast of Africa to the Island of Réunion.

The transmitting station was Nantes using two different wave-lengths—9 000 and 11 000 m. Although the method of measurement does not give the absolute values of the signal strength, the relative values are correct, and this is sufficient to determine the form of the attenuation curve and thereby the attenuation.

A sufficient number of night readings were taken to give a fairly well-determined average curve. A transmission formula of the type already found for day transmission fits the curve fairly well. The attenuation constant, as of course would be expected, is very much less than that found for day signals. Its value is 0·00068. This value is in good agreement with that determined for night transmission to Australia (Melbourne) and we may use it provisionally to determine the average values of night signals; by " average " is meant not only the average of a single night but of a period of, say, at least a month.

With this as a provisional basis we may go on to discuss long-distance transmission.

Bi-Directional Transmission.

The characteristics of long-distance transmission can be best explained as follows: the shadow line and the signal ray are both great circles on the earth's surface; therefore, half the ray path is always in darkness and half always in light. The transmission characteristics, however, depend on the relative positions of transmitter, receiver and twilight band.

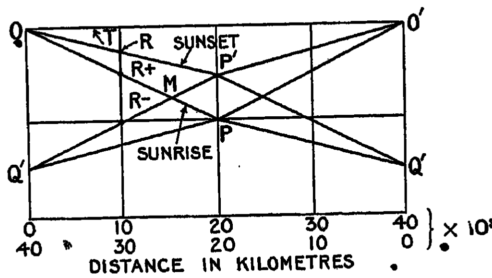


Fig. 100.

Except in the unique case where the receiver and transmitter are antipodal (i.e. at opposite ends of a diameter) there are three possible conditions, which can be illustrated by Fig. 101. Let PQRS be the signal great circle, T and R being the transmitter and receiver respectively, and let PMON be the shadow band. Then the shadow band may either cut the short segment TR once or not at all. In the latter case T and R

are either both in the light or both in the dark, so that the three conditions are:

(1) T and R both in light.
(2) T and R both in dark.
(3) One in light and one in dark.

ATTENUATION.

Under the conditions (1) and (2) the transmission, which is primarily dependent on the amount of light and darkness on the two paths, will remain constant for quite a considerable period of time, except when T and R are nearly 180° apart.

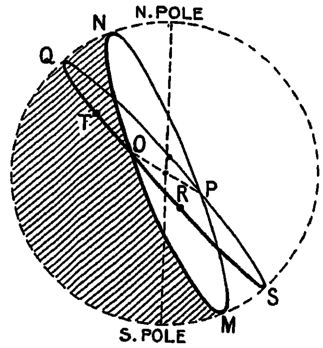


FIG. 101.

Under condition (3), however, the transmitted signals will rapidly alter, since the amounts of light and darkness on the paths are changing rapidly with the position of the twilight bands. The two more or less stable states occur, therefore, under conditions (1) and (2).

An examination of Fig. 101 will show that these states occur between sunrise at the receiver and sunset at the transmitter, and between sunset at the receiver

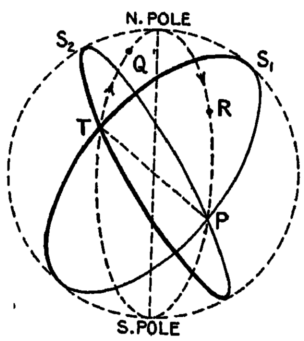


FIG. 102.

and sunrise at the transmitter, if R is less than 180° West of T, and vice versa if R > 180° West of T.

Under these conditions it is possible to state the total attenuation on the two paths without having to specify the exact time, and the comparison between observed and computed signal strength will, in general, be made at these stated times. It is the more natural to do this because the signals (*a*) are usually at their maximum at these times, and (*b*) are not complicated by the effect of crossing the shadow band, the effect of which is always difficult to allow for. We may therefore proceed to calculate the total attenuation under these two conditions.

The total attenuation (for a given wave-length), i.e. $\alpha d/\lambda^{\frac{1}{2}}$, can be plotted against distance, both for the daylight and night paths; the curves obtained will, of course, be straight lines. These are represented in Fig. 100.

For any given point on the globe there are two great circle distances to the transmitter, one less than 20 000 km and the other greater than 20 000 km, the sum of the lengths being, of course, 40 000 km. This is represented in Fig. 100 by the scales originating at the extreme left and extreme right respectively.

In the stable state, the short path (1) is wholly in light and the attenuation is represented by the ordinates

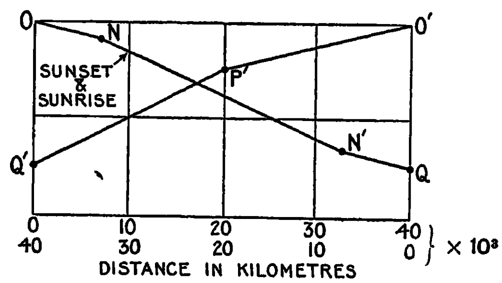


FIG. 103.

to OPQ, i.e. SR, and in Fig. 100 the slope of the line OP is α_1.

The long path is partly in darkness and partly in light, and the total attenuation, i.e. $\alpha_2(20\,000)/\lambda^{\frac{1}{2}} + \alpha_1(20\,000 - d)/\lambda^{\frac{1}{2}}$ is represented by the ordinate to the broken line O′PQ′, i.e. SR. Again, by the same reasoning, under condition (2) the absorption on the two paths will be represented by the ordinates to the lines OP′Q and O′P′Q′ respectively.

It will be observed that the signals by the two paths

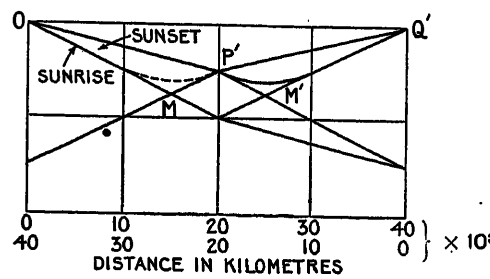


FIG. 104.

are equal at M and N with the values of α_1, and α_2 obtained by observations for relatively short-distance transmission is about 15 000 km from T by the shorter all-day path. At any point further than this the signals will prefer to come by the longer path, for they are on the whole less attenuated, since 20 000 km of this path is in darkness. At smaller distances than 15 000 km the signals by the short path are strongest.

An exceptional case occurs when the ray TR lies between TS_1 and TS_2, where TS_1 and TS_2 are the great circles of the shadow band at sunrise and sunset respec-

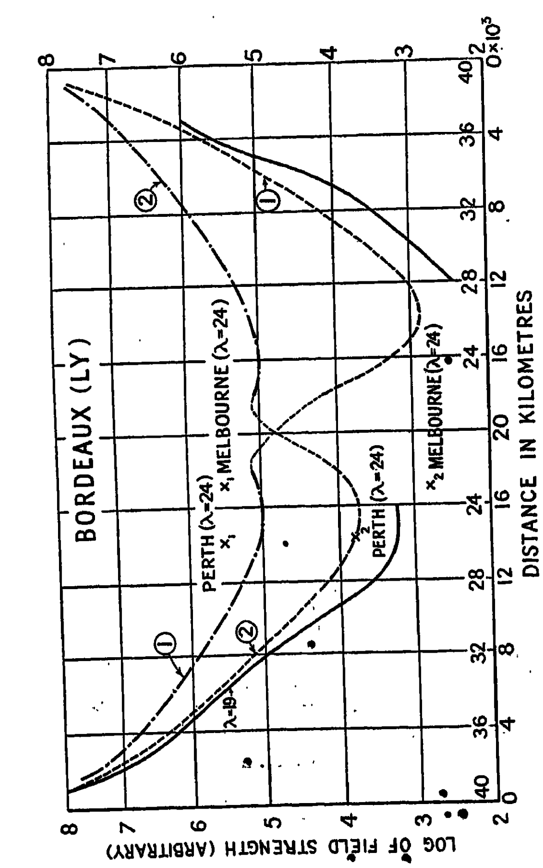


FIG. 105.

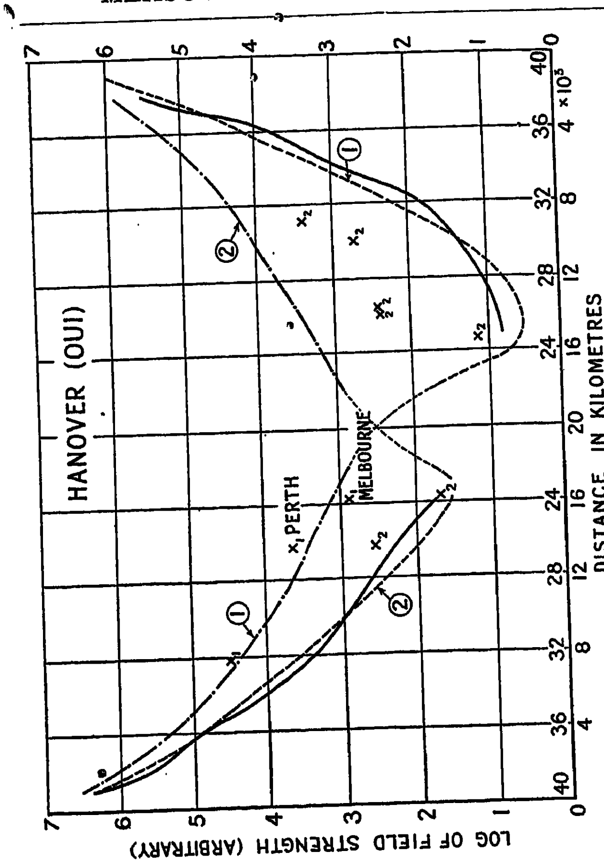


FIG. 106.

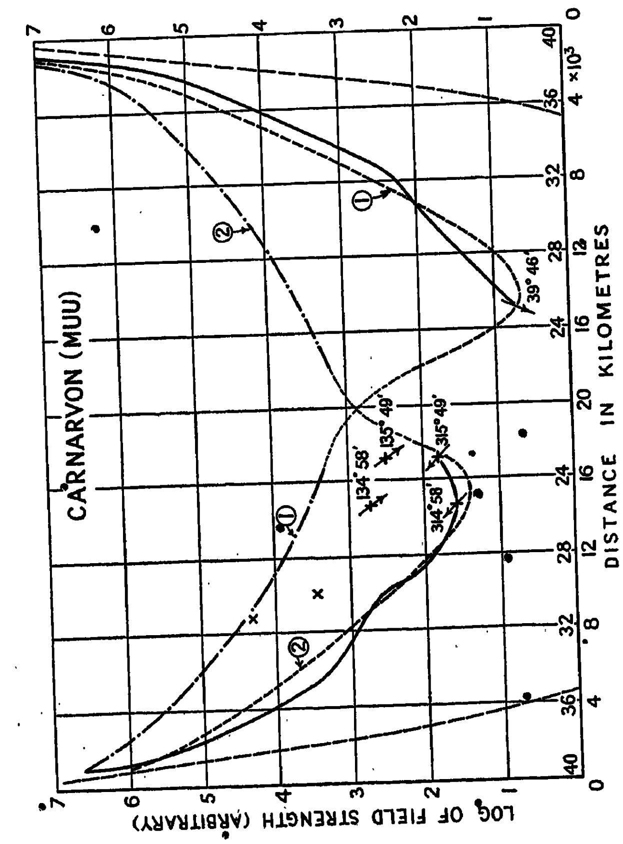


FIG. 107.

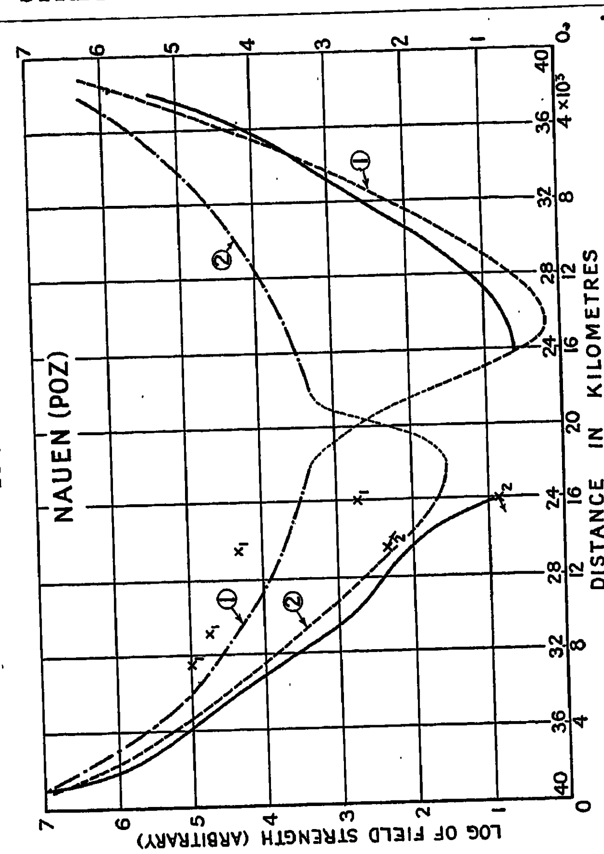


FIG. 108.

tively, so long as R lies on the short path beyond Q, where Q is on the same latitude as S_1 and S_2 (see Fig. 102). The shadow band cuts the arc TR whenever T is in darkness, so that the maximum* arc for which T and R are both in darkness is TQ and the corresponding absorption curve is ONN′Q (Fig. 103).

Apart from this exceptional case the two sets of curves OPQ, OP′Q, O′PQ′ and O′P′Q′ represent the absorption for West to East and East to West respectively for the occasions when the shorter arc between the receiver and transmitter is wholly in light or wholly in darkness.

The actual signal strength at M where the signals from the two directions are approximately equal will depend on the relative phase of the two sets of signals, and if this relative phase alters the apparent strength will alter. Since the actual paths of the rays pass through the upper atmosphere, where the effective electrical length of the paths may reasonably be expected to alter fairly rapidly, the relative phase of the two sets of signals will also alter and rapid pulsations of signal strength will occur. These fluctuations have actually been observed, originally by Messrs. Beverage and Rust at Rio, the signals being those from the American station Cavite, and almost simultaneously by Tremellen on the S.S. "Dorset" when it was in the Pacific about 13 000 km from the American stations, from which the effect was most marked.

It was possible to show that the signals came round the world in the two opposite directions by using a unidirectional receiver and receiving first one and then the other set of signals. With this receiver no fluctuations or beats were observed, since only one set of signals was received at a time and the interference between the two sets was avoided.

Returning to Fig. 100, it will be noted that the actual signals received under condition (1), for instance, are obtained from a combination of the curves OPQ and O′P′Q′, and in Fig. 104 the composite curves OMPO′ and OPM′Q′ have been drawn, which represent the sum of the signals from both directions.

In the region of M and M′ the strength is variable on account of fluctuations, but the actual curve represents the maximum value which occurs when the signals from the two directions are in phase; also along the branches MO′ and OM′ the signals are variable on account of the fluctuations which occur at night. To get the final curves, log $1/(R \sin \theta)^{\frac{1}{2}}$ is added to the ordinates of the previous curves, where R = radius of earth, and θ is the zenith angle between the two stations.

The ordinates will then, except for an additive constant, represent the theoretical values of log E, where E is the field strength in the signal, plotted against distance. The basis of this calculation is, of course, the assumption that signal E.M.F. can be represented by an expression of the form $\dfrac{AhIe^{-\alpha d/\lambda^{\frac{1}{2}}}}{\lambda(R \sin \theta)^{\frac{1}{2}}}$ (which was found to be correct for short-distance transmission), where α has the value α_1 or α_2 according as the ray is in light or in darkness. It neglects any variations which may be due to changes of α with latitude or direction of transmission of the signals. A comparison of the actual signals with the theoretical curves will then show up any deviations on account of effects.

Figs. 105 to 111 have been plotted in this manner. The plotted curves show the theoretical values calculated as above, the only alteration being that the day attenuation-constant on the West to East path is taken as 0·00107, whereas on the East to West path it is assumed to be 0·00160. The full lines represent the day mean-values, and it will be observed that only in exceptional cases do they diverge largely from the theoretical values.

The values taken on the S.S. "Dorset" in the Pacific are almost invariably greater than the calculated ones; this merely reflects the result before obtained, that the attenuation in the Pacific is less than in the Atlantic. The other divergences are due to the East and West effect at Melbourne and Perth, and are shown quite clearly on the curves for the American and long-wave stations, and Bordeaux. With regard to the American signals, the main feature is the absence of signals when the ray passes over the North and South Poles. The arrows indicate roughly the direction of signals, the vertical axis being taken as North and South.

It must be remembered that, as in the example given in Fig. 103, there is no moment during this period when the ray path is wholly in darkness, even though the length of the path is less than half the circumference. But even when the path was wholly in daylight, measurable signals should have been observed if they had been attenuated with the average value of α, and the absence of signals indicates the existence of very large values of attenuation somewhere on the path. The main features of long-distance transmission are shown up very well by this method of representation, and seem to us to leave little doubt that the assumption on which the theory is based is approximately correct.

Australian Signal Measurements.

A glance at Figs. 33 to 47 will show that the diurnal curves of the signal strength of the long-distance stations (i.e. European and American) are characterized by a double peak, the interval between the two maxima being approximately 12 hours. The peaks occur at times which are roughly those in which either the short path or the long path from the transmitter is wholly in darkness, i.e. under the conditions (1) and (2) referred to before. This is not strictly accurate, for no more than 20 000 km of the long path can ever be wholly in darkness. A more accurate statement is that the part of the path in daylight is a minimum at the other peak. Directional measurements show that the signals actually do traverse the darkened path, even though it may be considerably longer than the short daylight path.

The long-wave stations LY, at Melbourne and Perth, and WQL and WQK at Perth, are exceptions. The signals from these stations are in general practically entirely from West to East in all circumstances.

In the case of the shorter-wave stations, however, we are dealing almost entirely with night transmission.

These night or quasi-night readings differ in one respect from night readings taken at relatively short

* The cases where the transmitter or receiver is within the Arctic or Antarctic Circle are not considered, as they do not come within the range of practical working.

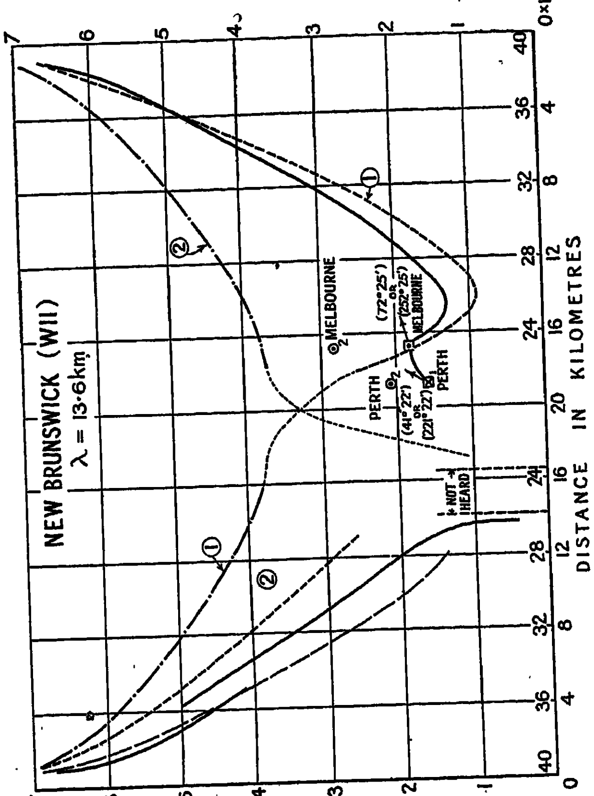


Fig. 110.

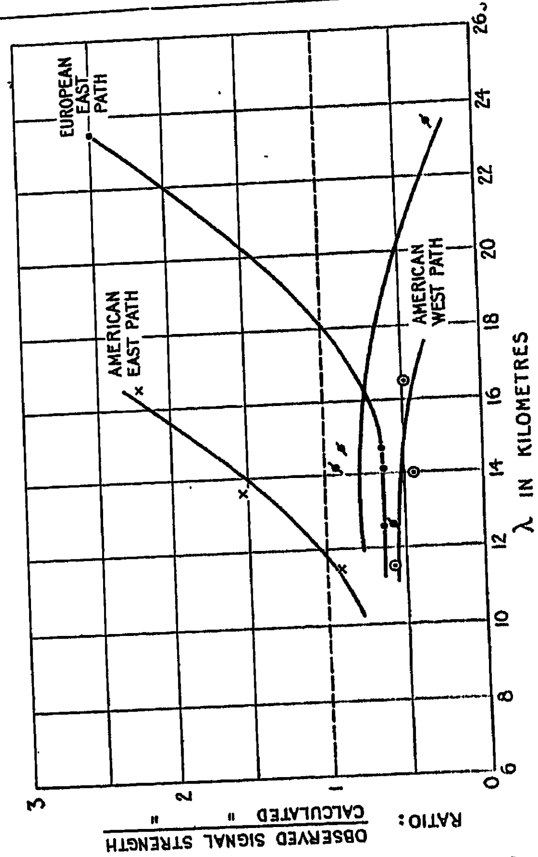


Fig. 112.

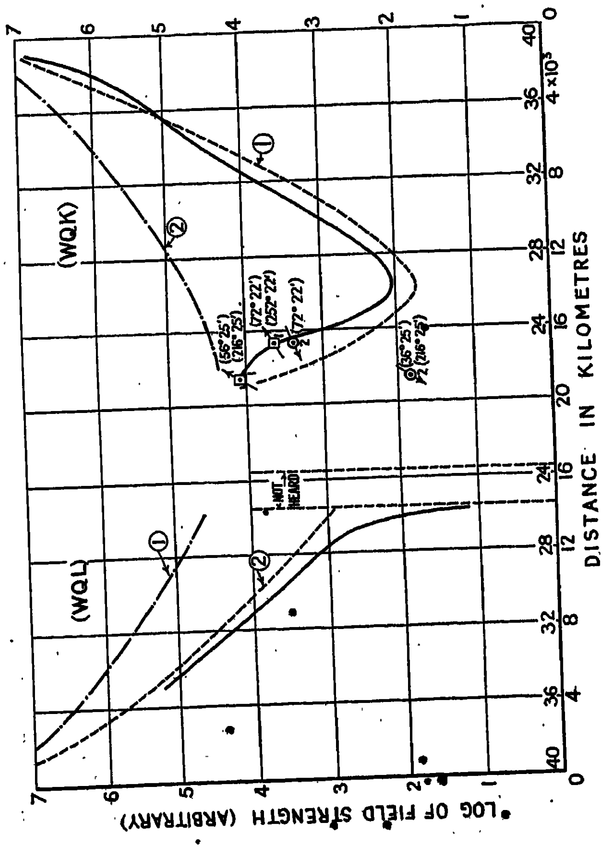


Fig. 109.

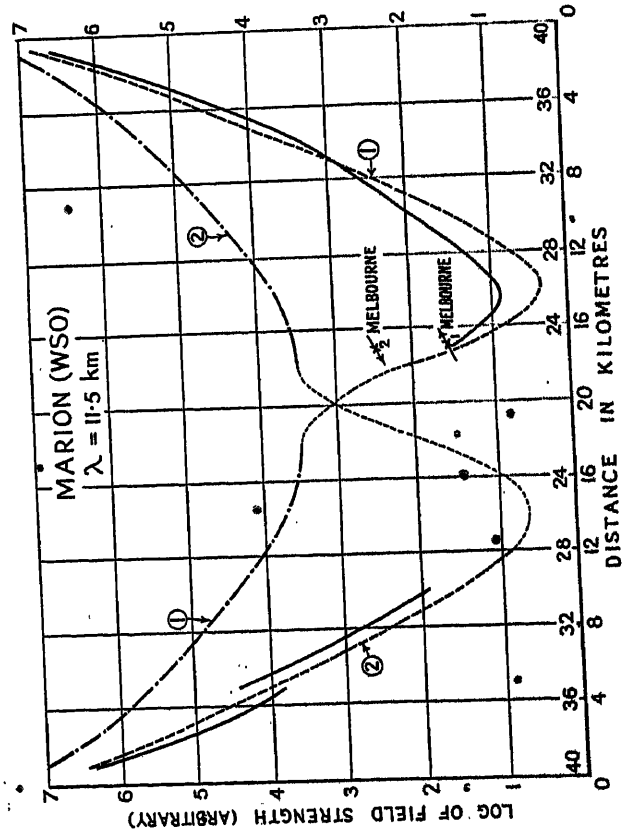


Fig. 111.

distances; they are very considerably less variable and the task of comparison with theory becomes correspondingly simpler.

We have seen that a transmission formula of the type already obtained for day transmission is also applicable in the case of night transmission. This is confirmed by the following method of setting forth the results. An examination of Table 15 brings to light the interesting fact that the maximum values of the signal strength measured at Melbourne for the shorter-wave stations are equal to the day signals (on the outward voyage) at a given shorter distance d_1, this distance being practically the same for all stations.

This means that if the day signals OUI, MUU and POZ at a certain distance d_1, which is approximately 6 500 km, are E_1, E_2, E_3, respectively, then the night signals at Koo-Wee-Rup, near Melbourne (approximately 17 000 km), of these stations are also approximately E_1, E_2, E_3. We can argue from these results that the attenuation over a distance of 6 500 km in the daytime is approximately equal to the attenuation over 17 000 km at night, except for the slight modification introduced by the different distance factors.

TABLE 15.

Table of Observations at Koo-Wee-Rup.

Station	Wave-length	E (obs.)	d_1	Actual distance to Melbourne
	km		km	km
Hanover (OUI) ..	14·7	17·1	6 000	16 290
Carnarvon (MUU) ..	14·1	12·2	6 500	17 100
Nauen (POZ) ..	18·6	18·8	6 800	16 000
American.				
Rocky Point (WQK)	16·45	30·8	9 700	16 750
Tuckerton (WGG) ..	15·9	18·75	—	16 700
New Brunswick (WII)	13·6	12·5	9 500	16 610
Marion (WSO) ..	11·5	11·25	8 800	16 940

Proceeding in this manner we get the following values for the night attenuation factor for West to East transmission of the European stations, i.e. $\alpha_N = 0{\cdot}000669$.

Again, the American stations transmitting from East to West give a value of $\alpha_N = 0{\cdot}000772$. These values, it will be seen, do not differ markedly from the attenuations derived from the night signal curve of Nantes, i.e. $\alpha_N = 0{\cdot}000677$.

It is not difficult to calculate the actual values of E when this attenuation constant is known, for we have

$$E = \frac{120\pi h I e^{-0\cdot000677 d/\lambda^{\frac{1}{2}}}}{\lambda(d_0 R \sin\theta)^{\frac{1}{2}}}$$

h, I, λ and d are known; if, therefore, we insert the known values of d_0, all the quantities on the right-hand side are known and E can be computed and compared with the observed results.

The assumption that d_0 is the same during the night as during the day is probably not justified but, in the absence of any reliable measure of the quantity, we may assume that it is. Table 16 gives the observed and calculated values of the peak values of the E.M.F. at Melbourne.

TABLE 16.

West to East Path, wholly in Darkness.

Station	Wave-length	E (obs.)	E (calc.)	Ratio obs./calc.
	km			
Bordeaux (LY)	23·45	170–366	107	1·6–3·4
Hanover (OUI)	14·7	17·1	25·7	0·622
St. Assise (UFT)	14·5	—	—	—
Carnarvon (MUU)	14·1	12·2	20·1	0·607
Nauen (POZ) ..	12·6	18·8	29·4	0·640
American Stations at (Koo-Wee-Rup) East to West Path, wholly in Darkness.				
WQK	16·45	31	64·1	0·484
WII	13·6	12·5	28·2	0·444
WSO	11·5	11·5	20·3	0·567

The effect of land absorption has not been included in these calculations. If we take account of this the calculated values would be rather smaller and the ratios nearer to unity. The limiting value of 50 per cent land absorption would make all the values close to unity (except, of course, in the case of Bordeaux).

These figures refer to the short-path night transmission. The calculation of the long-path E.M.F. is complicated by the fact that the signal must cross the twilight line dividing light and darkness. There is a considerable amount of evidence to show that this acts as a barrier. This is illustrated in the majority of the curves showing the diurnal variations of signal strength; also there is a very marked minimum in the half-light, half-dark period, as can be seen from all the diurnal curves. The conditions in East to West transmission are by no means regular; there is, however, a general tendency for the weakening of signals after sunset at the receiving station when the twilight band lies between the two stations.

The conditions which determine this minimum are rather complex, and are difficult to allow for. If we calculate the signal, neglecting this effect, we shall probably be inclined to over-estimate and, other things being equal, the signals would be less than the calculated values.

A glance at Tables 16 and 17 shows the unexpected result that, in the case of the long-wave station at WQK at Long Island at any rate, signals are actually considerably stronger than the calculated values by the West to East route.

These results are plotted in Fig. 112, in which the abscissæ are wave-lengths in km and the ordinates represent the ratio of observed signal strength to the calculated values. It will be seen at a glance that, in general, on the longer wave-lengths the signals going by the West to East path are in excess of what would be expected and those travelling in the opposite direction are in defect. The difference in the extreme case

TABLE 17.

Long Path.—European.

Station	Wave-length	E (obs.)	E (calc.)	Ratio obs./calc.
	km			
Bordeaux	28·45	12·5	32·5	0·4 say
Hanover	14·7	5·0	5·58	0·895
St. Assise	14·5	—	—	—
Carnarvon ..	14·1	4·59	4·97	0·924
Nauen	12·6	2·17	3·75	0·58
American.				
Long Island (WQK)	16·45	35·4	15·9	2·225
New Brunswick (WII)	13·6	9·65	6·3	1·53
Marion (WSO) ..	11·5	4·17	4·5	0·927

of Bordeaux is as much as 5 to 1, and can therefore hardly be attributed to errors of experiment.

The fact that Bordeaux has no peak at 0600 G.M.T., and that the longer-wave American stations are at least as strong by the long route, 23 400 km, part of which is in daylight, as by the short all-night path, is a very good proof of the existence of some factor favouring West to East transmission.

It appears therefore that not only is there evidence of this effect in daytime (*vide* attenuations in the East and West directions), but there is also strong evidence of it at night, where it is specially marked on the long wave-lengths.

The results at Perth (Western Australia) are in agreement with these in this respect, but they are still further complicated by the fact that the great circles from the American stations pass through the higher latitudes.

The results of the S.S. "Boonah" expedition, it will be remembered, indicate that transmission in the neighbourhood of the North and South Poles is particularly unfavourable. On this account the signals from the American stations are weaker than would be expected in the West to East direction, and very much weaker in the opposite direction.

The case of Marion is specially remarkable. It is the farthest North of all the American stations, and therefore the bearing at Perth is to a marked extent further North and South than the other stations. The ray from this station passes nearer the Poles than any of the others. The signals from this station at Perth are consequently so weak that they were only measurable in a very few cases.

The long-wave stations WQL and WQK exhibit this East and West effect in a very marked degree, for at Perth the long path and short paths are nearly equal, the latter place being only about 1 200 km from the antipodes of the American stations, yet the signals coming by the longer West to East path are many times as strong as those coming in the opposite direction. It is hardly worth while repeating the calculations in this case, for the added complication of relatively high-latitude transmission introduces a large measure of uncertainty, since the actual values of the attenuation in these latitudes are unknown.

The observed mean peak-values have all been plotted in Figs. 109 to 111, where the differences between the actual and theoretical curves due to East and West effect and Polar transmission can be seen at a glance. The differences are rather minimized in this method by the logarithmic scale. It has not seemed worth while to analyse the diurnal curves into their Fourier components.

The semi-diurnal nature of the signal strength, as well as its connection with the times of sunrise and sunset at the end stations, is obvious enough, but perhaps the following ideal form calculated on the basis of a fixed attenuation for day transmission, and another fixed value for night transmission, may not be without interest. It reproduces in its rough feature the general form of the diurnal curves where they are not complicated by unidirectional effects (see Fig. 113).

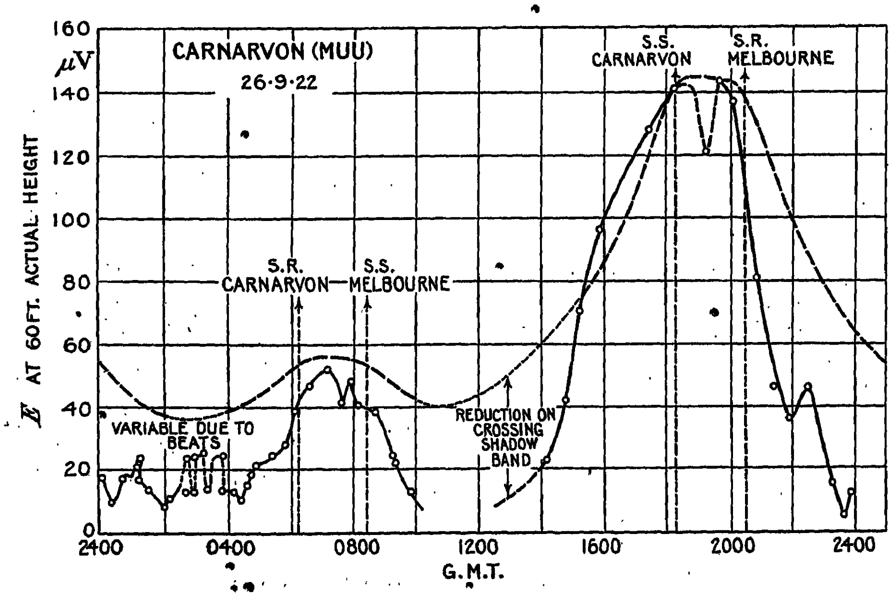


FIG 113.—At Koo-Wee-Rup. (Effective height = 12 metres.)

It will be observed that during the period in which the ray is half in light and half in darkness (i.e. 1200 and 2400 G.M.T.) the signals are actually considerably less than would be expected on the pure attenuation theory. This is no doubt only another example of the weakening of signals which occurs when they pass from day to night, and vice versa, which has already been commented upon. This effect is illustrated very clearly in Fig. 80, which shows the diurnal variation of signal strength of the European stations near the Maldive Islands.

Theoretical Conclusions.

The observations which have been analysed in the preceding sections show very clearly that the basic formula for both day and night transmission is of the Watson type, i.e.

$$\frac{AhIe^{-ad/\lambda^{\frac{1}{2}}}}{\lambda(R\sin\theta)^{\frac{1}{2}}}$$

where a is practically independent of the wave-length but may vary with latitude, local conditions, etc.

It therefore seems very probable that the assumption on which this type of formula is based, i.e. of an outer conducting layer, is approximately correct, and it is a matter of considerable interest to see whether the Heaviside layer theory can give any explanation of such facts as the difference between day and night transmission, the local variation of the attenuation constant, and seasonal effects, etc. To begin with, the theory in its original form needs modification and the assumption of a definite reflecting layer cannot be justified. For if we make such an assumption we are led into difficulties.

On the Watson theory the attenuation constant may be calculated from the resistivities of the upper and lower conducting layers and their distance apart, by means of the formula

$$a = \frac{1}{2H}\left\{\left(\frac{\rho_1\mu_1}{2c}\right)^{\frac{1}{2}} + \left(\frac{\rho_2\mu_2}{2c}\right)^{\frac{1}{2}}\right\}$$

Now we can estimate the height of the layer to be somewhere between 30 and 100 km. With any value of H between these limits we find that $\frac{1}{2H}\left(\frac{\rho_1\mu_1}{2c}\right)^{\frac{1}{2}}$ which is the contribution of the earth's or sea's resistivity to the attenuation (where $10^{11} < \rho_1 < 10^{13}$) is very small compared with the total observed attenuation coefficient.

We must therefore assume that, at any rate in over-sea transmission, practically the whole of the attenuation is due to the resistivity of the upper layer. This being the case, the observed value of attenuation, a_0 say, gives us a relation between the resistivity of the upper layer and the height of it above the surface of the earth, for

$$a_0 = \frac{1}{2H}\left(\frac{\rho_2\mu_2}{2c}\right)^{\frac{1}{2}}$$

where μ_2 is assumed to be unity and ρ_2 and H are the only two unknown quantities. If we assume the same limits for H we get limiting values for ρ_2 as well. Taking a as 0·0015 we find the limits to be $4{\cdot}9 \times 10^{13}$ and $5{\cdot}4 \times 10^{14}$ C.G.S. units.

Now it can be calculated that a well-defined layer of this resistivity acts as a nearly perfect reflector for radio waves with wave-lengths lying between 6 and 25 km, even for normal incidence.

It follows that a receiver situated, say, between 100 and 200 km from a transmitter should receive, even during the daytime, nearly as much energy by the reflected ray as by the direct ray. The reflected ray makes an angle of something like 45° with the surface of the earth. Now various observations show, without any sort of doubt, that such "high-angle reflection" is wholly absent in the daytime, and we should be inclined to put the limiting angle at about 3° or 4° at the most.

The difficulty involved here can be removed by assuming that the layer acts as a good reflector for glancing incidence, say, but as a very poor reflector for normal incidence. A layer with an ill-defined under surface will act in this way. For example, if we assume that the conductivity is zero below a certain height and has a constant gradient above this height, then the reflection coefficient (assumed small) will vary as $1/\sin^3\theta$, the gradient of conductivity, and the square of the wave-length, i.e.

$$\frac{(\sigma_1\lambda^2 c)}{8\pi\sin^3\theta(2\pi)^2}$$

where σ_1 = gradient of conductivity.

It is, of course, questionable whether a layer of this sort will attenuate the waves in just the same way as a well-defined layer. The attenuation factor will probably not be exactly of the form $ad/\lambda^{\frac{1}{2}}$ but will depend on the nature of the gradient of conductivity in the layer.

The example of a layer with uniform gradient of conductivity above a certain height may be used to show that the attenuation factor is not altered to any great extent by the assumption of an ill-defined layer.

We have found it possible to calculate the absorption suffered by a plane wave travelling between the earth and such a layer, on the assumption that both are bounded by plane surfaces, which, in the light of Watson's analysis, seems sufficiently accurate, and we have found an attenuation coefficient of the form

$$\frac{A}{H}\cdot\frac{1}{(\lambda^2\sigma_1 c)^{1/3}}$$

where σ_1 is the gradient of conductivity, A is a constant, and H = height of layer above earth's surface.

It varies as $1/\lambda^{2/3}$ instead of as $1/\lambda^{\frac{1}{2}}$, but the observations do not cover a sufficient range of wave-length to decide which is the most accurate formula. It seems probable that the formula of the Watson type is sufficiently accurate even in the case where the upper surface is ill-defined.

Height of the Upper Layer.

The measured values of the quantity d_0 in the formula

$$E = \frac{120\pi hIe^{-ad/\lambda^{\frac{1}{2}}}}{\lambda(d_0 R\sin\theta)^{\frac{1}{2}}}$$

throw some light on the "effective height" of the Heaviside layer in the daytime. A rough way of determining this is the following:

In view of the fact that high-angle reflection is absent, let us suppose that the energy radiated within a cone of angle θ (see Fig. 87) is reflected, but that higher-angle transmission than this is absorbed or, anyhow, not reflected.

The energy radiated within this cone is :

$$W = \frac{\int_0^{\theta_1} \cos^3 \theta d\theta}{\int_0^{\frac{1}{2}\pi} \cos^3 \theta d\theta} \cdot \frac{40(2\pi)^2 h^2 I^2}{\lambda^2}$$

or $$W = \frac{40(2h)^2 h^2 I^2}{\lambda^2} \times \frac{3}{8}\left(3 \sin \theta_1 + \frac{1}{3} \sin 3\theta_1\right)$$

and when θ_1 is small is

$$\frac{3}{2}\theta_1 \times 1\,600(hI/\lambda)^2 \text{ watts.}$$

If we assume, as before, that this energy is radiated through an annulus of area $2\pi R(\sin \theta)H$ (see Fig. 87), since the energy radiated per unit area is

$$\frac{1}{4\pi} \cdot \frac{E^2}{c} \text{ ergs} \quad \text{or} \quad \frac{1}{4\pi} \cdot \frac{E^2}{c} \times 10^{-7} \text{ watts}$$

$$\frac{2\pi R(\sin \theta) H E^2 \times 10^{-7}}{4\pi c} = \frac{3\theta_1 \times 1\,600 h^2 I^2}{2\lambda^2}$$

or $$E = \frac{120\pi h I}{\lambda[(\frac{1}{2}H/\theta_1) R \sin \theta]^{\frac{1}{2}}} \text{ volts/cm}$$

so that $d_0 = H/(2\theta_1)$.

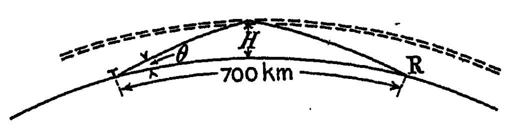


FIG. 114.

If we assume that reflection begins to be appreciable at distances > 700 km, we have another relation between H and θ. Taking $d_0 = 380$ km, we get $\theta = 3°$ and $H = 32{\cdot}1$ km (see Fig. 114). Of course the assumption of a definite limiting value of θ beyond which there is no reflection is not justified, but the method gives a value of θ which is within the limit determined by experiment, and the method may be considered to give at least a rough approximation of H.

There is another method which is based on an investigation of the propagation of waves from a radially symmetrical transmitter situated between two perfectly conducting planes, by which we can determine the equivalent height of the layer.

Thus suppose T is the transmitter situated on the lower surface; then on account of the reflection at the upper and lower conductors the electric force at R, say, is the same as that due to T, and comprises an infinite series of images spaced uniformly along an axis through T and perpendicular to the two planes, a distance $2H$ apart (see Fig. 115).

The sum of the electric and magnetic forces at R can therefore be expressed as an infinite series of terms, each term being due to one of the images. When the distance TR is large compared with H and with the wave-length, the series is so slowly convergent as to become absolutely unmanageable, but it can be transformed by a mathematical device into an integral which, in certain cases, can be simplified into quite a manageable form. A full discussion of this problem is beyond the scope of this paper, but certain results may be generalized so as to be applicable to the case under discussion.

It is generally assumed that at large distances from the transmitter the wave is approximately plane, with the electric force vertical and uniform between the conducting layers, the high-angle reflection having been cancelled out, so to speak. It can be shown that this "normal" state of affairs exists only when H is less than half a wave-length, in which case the electric and magnetic forces in the wave-front can be calculated with sufficient accuracy from the formula

$$E = \frac{120\pi h I}{\lambda[(4H^2/\lambda)r]^{\frac{1}{2}}}$$

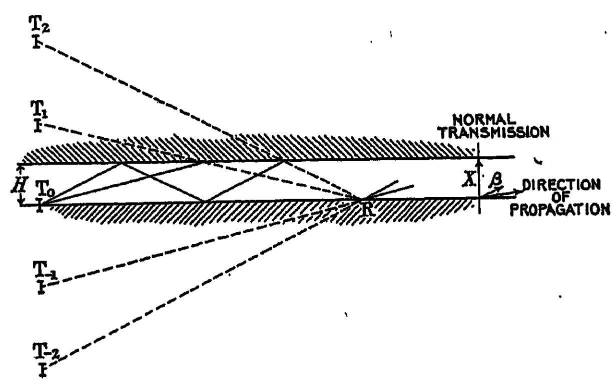


FIG. 115.

where r is the distance from the transmitter and the other quantities are the same as in the previous formulæ.

It will be observed that the electric force E varies as $1/r^{\frac{1}{2}}$, which is the appropriate factor for cylindrical transmission. When the height of the layer is greater than $\frac{1}{2}\lambda$ the state of affairs is entirely altered. High-angle reflection appears and swamps the normal wave, and when the layers are perfectly conducting the wave never settles down to the normal state but goes ricochetting from floor to roof indefinitely. This state, however, is only a consequence of the assumption of absolutely perfect conductivity in the reflecting layers. But we have seen that the actual layer is by no means perfectly reflecting, and probably has such an ill-defined undersurface that there can be no high-angle reflection. Under these circumstances even when $H > \frac{1}{2}\lambda$ the normal state of affairs obtains and the E.M.F. can be calculated from the formula

$$E = \frac{120\pi h I e^{-\alpha d/\lambda^{\frac{1}{2}}}}{\lambda[(4H^2/\lambda)r]^{\frac{1}{2}}}$$

Comparing this with the actual Watson-type formula and replacing r by $R \sin \theta$ on account of the spherical

nature of the actual reflecting surfaces, we can indentify d_0 with the quantity $4H^2/\lambda$.

Now it will be observed that, in Fig. 92, where d_0 is plotted as a function of λ the summer values of d_0 are very approximately inversely proportional to λ. The winter values decrease rather more rapidly than this. Assuming d_0 to be 400 for $\lambda = 16$, we get the value of H thus

$$\frac{4H^2}{16} = 400\,; \quad H^2 = 1\,600\,; \quad H = 40\,;$$

which is in fairly good agreement with the approximate value previously obtained.

The winter values of d_0 are rather higher than the summer values, suggesting a greater value of H_0. Summarizing, we may fairly safely conclude that in the daytime there exists a conducting layer at a height somewhere between 30 and 40 km. This layer has a very ill-defined under-surface and acts as a good reflector for a glancing incidence but as a very bad reflector for large angles of incidence. The height of the layer is probably greater in winter than in summer.

It is interesting to note how well this purely radio evidence agrees with the evidence derived from other sources, i.e. the study of terrestrial magnetism. Briefly, S. Chapman, who has worked out the subject very thoroughly on the basis of terrestrial magnetism, has concluded from the evidence afforded by the diurnal and lunar magnetic variations that there exist two conducting layers: (*a*) the permanent auroral layer, extending over a height of approximately 80 km to 300 km, and (*b*) a lower layer present only in the daytime. The latter is probably due to the ionizing effects of the sun's γ radiation. Its height will naturally depend on the zenith distance of the sun, i.e. the angle of incidence of the sun's rays.

For normal incidence the maximum conductivity in this layer should occur at a height of about 26 km, tailing away to one-tenth of its value at 18 and 45 km. At grazing incidence the maximum intensity should occur at a height of 50 km. The height determined from radio measurements is well within these limits.

Day and Night Transmission.

The difference between day and night transmission is readily explained on this theory. Transmission during the daytime is confined to the space between the earth and the lower conducting layer, which we may consider to be practically impervious to the long radio waves. (S. Chapman gives the average conductivity of this layer as 25×10^{-6} C.G.S. units. Radio waves would be entirely absorbed in travelling a very short distance through such a medium.)

At night when the ionizing agent, i.e. the sun's γ radiation, is removed, the ions re-combine, the lower conducting layer disappears and the upper permanent auroral layer comes into play. We must assume, both from radio and auroral evidence, that this has a much better defined under-surface and that it can reflect radio waves at much greater angles of incidence than those which exist in the daytime.

As a consequence we get the irregular interference phenomena which are so characteristic of night transmission and which must be due to slight variations in the height and conductivity of the layer. The night distortion of bearings taken with the ordinary frame type of aerial is also explicable on this theory,* as well as the absence of distortion in daytime. A theory developed on these lines has already been given by one of the authors in the *Radio Review*, and additional evidence of a very convincing nature has also been given by G. M. Wright and S. B. Smith in the same publication.

At the risk of repeating what has already been said in these articles, it will be well to consider this theory in the light of the present evidence, which seems to the authors to supply one of the missing links in the previous argument. Thus the distortion of bearings at night was attributed to the action of high-angle reflected waves polarized with the electric force horizontal and the magnetic force in the vertical plane but perpendicular to the ray. The manner in which this acts in producing distortion of the apparent direction of the ray is sufficiently obvious to require only passing comment here, and may be briefly described by reference to Fig. 116. Let OP be the direction of the ray;

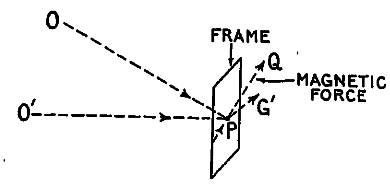


Fig. 116.

then PQ may be considered to be the direction of the magnetic force, the electric force being perpendicular to the paper.

If a vertical frame is erected at P the plane of which is perpendicular to the plane of the paper, it would normally receive no signals from the direction O′P, and would therefore give the correct bearing.

If, however, the ray OP is present the magnetic force PQ is linked with the frame, and a signal will be received notwithstanding the fact that the plane of the frame is perpendicular to the plane of the rays OP and O′P.

The actual position of the frame for minimum signals will depend then on the relative intensities and phase of the rays OP and O′P. It will be observed that the conditions for the production of this distortion are:

(1) That the ray should make an appreciable angle with the earth's surface (i.e. high-angle reflection must be present).

(2) That there should be a component of the magnetic force polarized in the vertical plane.

If either of these factors is absent no distortion of bearing should occur due to this cause. The absence of the distortion in daytime was attributed in the previous paper to the assumed existence of an ill-defined layer present in the daytime which could not reflect high-angle waves at all. The actual existence of such a layer has now been confirmed by the evidence of radio signals and of terrestrial magnetism, and another link

* *Radio Review*, 1921, vol. 2, pp. 60 and 231.

in the argument may be considered to be firmly established.

It may be as well to mention here that bearings taken at great distances at night have been almost invariably correct and free from night distortion. Sufficient explanation of this may be found in the fact that in order that signals may arrive at B, say, with a high-angle incidence, the ray must proceed by many reflections, and the higher the angle of incidence the greater must be the number of reflections. As a considerable amount of energy is lost at each reflection it is probable that the high-angle rays disappear after a few reflections and leave the normal ray undisturbed (see Fig. 117).

Local Variation of Attenuation.

On this theory the attenuation suffered by the wave in daytime is a function of the height of the layer and the gradient of conductivity in the layer. These quantities will vary with the latitude, for they are functions of the angle of incidence of the sun's rays, which depends on the latitude and also on the season. Seasonal changes and also changes with latitude are therefore to be expected.

The form that the variation with latitude will take depends on the two factors: (1) the mean height of the layer, and (2) the gradient of conductivity, as well

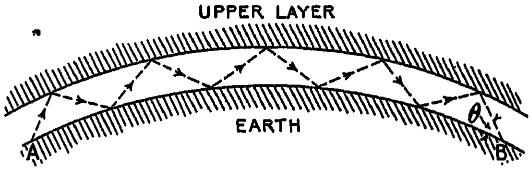


Fig. 117.

as the actual conductivity in the layer. The height should be greater at high latitudes, and the attenuation consequently less on this account. The nature of the change in the second factor is not clear, but it certainly appears to be the determining factor and to increase the attenuation at high latitudes.

It is arguable that the resistivity of the lower layers will be greater because the ionizing agent, i.e. the sun's radiation, will have further to penetrate through the atmosphere when the rays come in at almost glancing incidence, and that the attenuation will therefore be greater.*

The observational material is not sufficient to determine the exact variation of α with latitude, but it is certainly sufficient to suggest that the attenuation is greater at high latitudes and less at lower ones. If it be assumed that the height and nature of the layer is merely a function of the angle of incidence of the sun's rays, there should be a connection between the seasonal change of α and the change of α with latitude. A change from summer to winter should be equivalent to the alteration produced by an increase in latitude. There exists a certain amount of evidence that this is the case. Transmission in winter is worse than in summer, and consequently transmission in high latitudes should be worse than in low ones, as is the case.

* S. Chapman finds that the mean resistivity in the winter, as determined by magnetic observations in England, is considerably greater than that in summer.

Beats.

There can be no doubt that this effect is primarily caused by the interference of signals travelling both ways round the world, for the experiments with the unidirectional or heart-shaped "receiver" cannot be interpreted otherwise. There are, however, so many possible ways in which this interference may be varied so as to cause the beats observed, and so little experimental evidence beyond the actual observation of these beats, that their ultimate cause is still uncertain.

Let us consider the possibilities in detail. Suppose we call the waves which arrive at the receiver by the two great-circle paths, A and B respectively, then we may think of the system comprising the transmitter, earth and receiver, as a gigantic Michelson interferometer. The waves from the source at S follow the two paths SPR and SQR and interfere at the receiver R, and all the experimental evidence allows us to infer is that the relative phase of A and B at R is changing.

When R is not at the antipodes of S, i.e. when the paths SPR and SQR are not equal, the signal arriving by the longer path will be delayed relatively to that which comes by the shorter path, and if the difference is as much as 10 000 km the delay will amount to at least as much as 1/30th second. With high-speed signalling the dots from the two directions will hardly overlap at all and may cause the unreadability which is a characteristic of the beat effect. This effect, of course, will not appear at or close to the antipodes.

Another effect which also depends on the inequality of the two paths, but which does not depend on the speed of sending, is the resemblance which the system bears to a large interferometer. If we could view the electric intensity from the outside of the world we should be able to see a series of interference bands, spaced about half a wave-length apart and roughly forming circles about the antipodes. In the case of absolute symmetry this should be the case, but actually the position and intensity of the bands will be distorted by local variations, light and darkness, etc.

If the position of these interference bands changes, then from the point of view of an observer situated on the surface of the earth this shifting will appear as a waxing and waning of signal strength, in fact as beats. As before stated, the bands are approximately half a wave-length apart. Any variation of the wave-length of the transmitter will therefore cause the bands to contract or expand according as the variation is a decrease or increase of wave-lengths. Hence any change of wave-length of the sources will result in beats at the receiver.

In the case of absolute symmetry the antipodes is a place where all the electric forces are in phase whatever the wave-length; hence the bands contract and expand about this point.

For a given change in frequency of the transmitter the rapidity of the beats will be proportional to the distance of the receiver from the antipodes. If this distance comprises N half wave-lengths, i.e. $d = N\frac{1}{2}\lambda$, and if the wave-length alters by the amount $\delta\lambda$ in the time δT, then any given interference band which is originally at the source will move an amount $N\delta\lambda/2$

and therefore the number of bands which cross the receiver in the time δT is $N\delta\lambda/\lambda$ and the rate of the beats will therefore be $(N/\lambda)(\delta\lambda/\delta t)$. N may be as great as 1 000 so that $(1/\lambda)(\delta\lambda/\delta t)$, i.e. the percentage rate of change of λ, need only be 1 in 1 000 to produce beats of 1 per second.

The effect would therefore be quite observable on alternator or arc stations. This effect is again negligible at or close to the antipodes. Apart from these effects there are two other possibilities depending o ieal variation of the effective electrical length of the two paths: (*a*) the interference bands may shift irregularly about a given mean position, in which case the mean frequencies of the waves along the two paths are equal, but there will be irregular changes of relative phase; and (*b*) the interference bands may wander continually in one direction and never return. This implies a real difference in frequency between the two waves A and B.

With regard to alternative (*a*), this irregular shifting of the bands may be due to any irregular movements in the conducting layer which would tend to shorten or lengthen the effective electrical length of either path; changes in density or refractive index due to ionization, pressure-changes, etc., will all have an effect in altering the time taken.

Alternative (*b*) requires rather more consideration, for a real difference in frequency between the two paths seems rather difficult to believe. The effect is nevertheless possible, but only where there is some movement relative to the earth. The authors think that they are correct in their interpretation of the principle of relativity when they assert that the rotation of the earth as a rigid body cannot introduce any changes in frequency in the two paths as measured by an observer fixed on the surface of the earth. But there may be movements in the upper atmosphere, depending on the rotation of the earth relative to the sun, which might produce effects of this kind. For instance, the Heaviside layer in the twilight regions (at S, say, in Fig. 118) is probably inclined at an angle to the tangent at the earth's surface. This layer acts as a reflector and is moving relatively to the earth's surface at some $\frac{1}{2}$ km per second. The reflection of the ray at this moving mirror will produce a Doppler effect, the amount of which is given approximately by the formula

$$\frac{\delta n}{n} = 2 \sin \theta \sin \phi \frac{v}{c}$$

where v is the linear velocity of the moving layer, i.e. about $\frac{1}{2}$ km per second. If we assume n to be about 20 000, i.e. a 15-km wave, δn comes out at the order of 1/30, i.e. one beat every 30 seconds. This is certainly less than the average rate observed, which may be as fast as slow morse sending.

In connection with the East and West effect the hypothesis was entertained that there was a rapid drift of positively charged particles from East to West. Such a movement, if it existed, would tend to produce a change in the measured frequency for the ray which passes through this drift. The amount of change of frequency can only be guessed at, for it depends on factors which cannot possibly be measured at the earth's surface, but it seems to be within the bounds of possibility that sufficient change might be produced to account for the observed effects.

It may be noted that Mr. Rust has, in a very carefully performed experiment, actually observed these beats in England. Signals from WQK (Long Island, New York) were actually received in England the long way round, i.e. from the East, and were made to interfere with the residual signals from the West, obtained by setting the heart-shaped receiver with its blind spot facing very nearly the normal direction of reception. The authors understand from him, however, that the experiment is by no means easy and it should be carried out only when reception conditions are good and "strays" are not troublesome.

Much remains to be done in connection with this subject, which has very considerable interest from the theoretical point of view, but any experiments devised to determine whether there is a real change of frequency in the two directions will obviously be difficult to carry out.

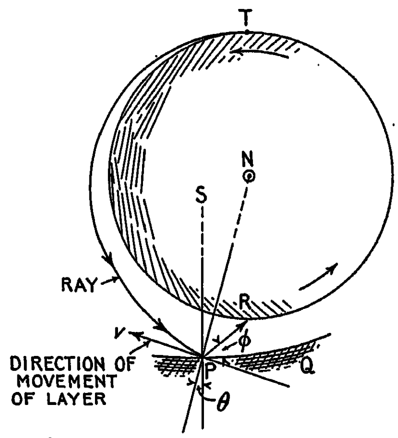


FIG. 118.—Path of ray TPR.

There are some indications that the beat effect is due to the variability in actual transmitted frequency and is not due to any real change in the frequency on the path, for UFT, which is a bad offender in this respect, shows "beats" to a marked degree. Also the fact that beats are not observed on a steady dash suggest that their absence is due to a steadying of the transmitted frequency on a long dash. The receiving station at Perth is close to the antipodes of the American stations, and hence the "beat effect" should be small on these stations.

Actually such effects were difficult to observe on these stations; on the long-wave stations, on which the effect might have been heard, the bi-directional effect only lasted a short time, and the shorter-wave stations, in which the bi-directional effect was of much longer duration, were swamped by X's.

The fact that it could not be definitely stated that beats were heard on these stations rather suggests that the variation of frequency at the transmitter is responsible for these effects.

EAST AND WEST EFFECT.

We have had occasion to note more than once in the course of this paper that transmission in a West to

East direction seemed better than transmission in the opposite direction. By this we mean the undoubted fact that, in every case that was examined, transmission in the West to East direction has been as good as or better than transmission in the opposite direction, whether by day or by night. But it must be very carefully pointed out that this does not necessarily imply that in every case West to East transmission is the better.

For instance, we have evidence that transmission from Europe to Australia on very long waves, e.g. Bordeaux, is better by the short West to East path than by the opposite one, but it would be very risky to state on this evidence that transmission from Australia back to England over the short European path will be unfavourable merely because it is an East to West transmission.

The case of transmission across the Atlantic is the only one in which we have evidence that transmission from America to England, i.e. West to East, is better than transmission over the same path from England to America, i.e. from East to West, and even in this case the difference in attenuation on what may be called the direct and return paths is not very great, and its existence may perhaps be doubted. Except for this case the differences can be attributed, we think, to local and seasonal variations of the attenuation. It must, however, be admitted that it requires considerable ingenuity to do so. If we take a map of the world and mark the routes with the various attenuation constants found for these routes, as in Fig. 119, we shall find that it is possible, except perhaps in the Atlantic, to fit the values in without assuming a different attenuation for a go and return path.

It will be found that except for the isolated case of NBA the high values of α occur in the North Atlantic and low values elsewhere, and although there is apparently a very marked change amounting almost to discontinuity to the East of England, this may be partly due to a change of α with season, for the attenuations to the East of England were observed in the summer months and those to the West in the winter months.

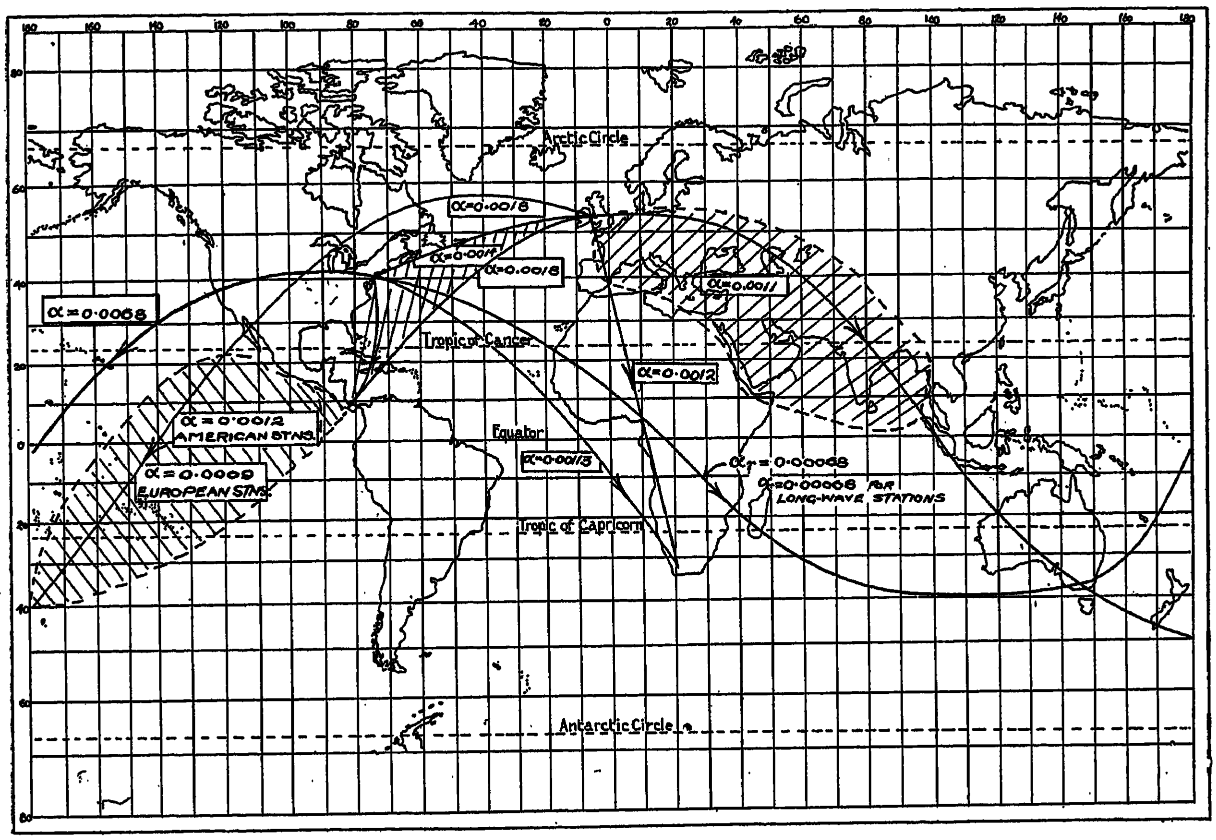


FIG. 119.

On the other hand, it seems more than a coincidence that, in every case so far examined, transmission from West to East has been better than that in the opposite direction.

From the point of view of theory it comes as rather a shock to have to admit the possibility that transmission from A to B, say, may be better than from B to A. Such a possibility seems to contradict the usual reciprocal relations of optics. This is a very general theorem due, we believe, to Helmholtz, which when applied to radio transmission can be translated into radio language in the following terms: If A and B are any two radio stations, however situated, then if they are both working on the same wave-length the E.M.F.

induced in A by unit current in B will equal the E.M.F. induced in B by unit current in A. For example, if we have two equal transmitting stations in England and Australia, then, at a given moment, the field strength produced by the English station in Australia should be equal to the field strength produced in England by the Australian station. If, however, we admit the accuracy of the transatlantic experiments, we shall have an actual case in which this theorem is contradicted.

It must be realized that this theorem is based on the assumption that all effects are linear, i.e. that the state of the field and every relevant quantity in the field (e.g. motion of the ions, electrons, etc.) is a linear function of the currents in the transmitting stations. It is possible to construct an example in which this linear relation is not obeyed, and it therefore follows that a real East and West effect is possible. The authors believe that examples in optics of the violation of this reciprocal relation are well known, but the example chosen here is more relevant to the subject under discussion, and may contain the germ of the explanation of the supposed East and West effect.

When a radio wave passes through a medium containing free ions or electrons these will be set in motion by the electric force. Suppose that the electric force is vertical, and the magnetic force horizontal; then the electric force will set the electrons in motion in a vertical direction, but on account of the vertical motion the magnetic force will produce a force on the electron which is perpendicular to both the magnetic field and this direction of motion, which is therefore in the direction of propagation. When the electric field is reversed the magnetic field is also reversed, the two being in phase, and the force on the electron is still in the direction of propagation. There is consequently a continuously acting force tending to drag the electrons along in the direction of propagation of the ray, and this is in the same direction even when the electromagnetic forces in the wave-front are reversed. The forward drift of the electrons must therefore be a function of the square of the magnetic field strength, and the linear relation no longer holds.

J. J. Thomson has shown how to calculate the actual amount of absorption suffered by a radio wave when passing through a cloud of electrons. As explained, the waves set the electrons with a forward drift the velocity of which can be calculated from the formula

$$c^2 - (c - \omega)^2 = \left(\frac{\lambda}{2\pi}\right)^2 \frac{e^2}{m^2} H_0^2$$

where c = velocity of light,
ω = velocity of drift of the electrons,
λ = wave-length,
e = charge,
m = mass of ion, and
H_0 = magnetic field in the wave-front.

When ω is small compared with c, as is usually the case,

$$\omega = \frac{1}{2c} \cdot \frac{\lambda^2}{(2\pi)^2} \cdot \frac{e^2}{m^2} H_0^2 \text{ (approximately).}$$

These ions have energy, to gain which they have to rob the energy of the wave, and the attenuation constant introduced is equal to

$$\frac{N\lambda^4 e^4}{128 m^3 \pi^4 c}\left(\frac{E}{300}\right)^2$$

where E is the voltage per cm in the wave-front. It varies as the fourth power of the wave-length and the square of the magnetic or electric force in the wave-front.

The way in which this effect may be used to explain the existence of a change of attenuation when the direction of propagation is reversed is as follows: Suppose there is a drift of ions or electrons along the direction of the ray. If the drift is in the same direction as the propagation of the waves, the time it takes for a wave to pass one of the ions or electrons is increased in the ratio of $1 + (v/c)$ to 1, where v is the velocity of drift, and hence, since the absorption is proportional to H^2T^4, we find that the absorption is increased in the ratio of $(1 + v/c)^2$ to 1 (approximately). If the direction of propagation is opposite to that of the drift the attenuation will be reduced in the ratio of $(1 + v/c)^2$ to $(1 - v/c)^2$. It will be observed that it requires very high velocities of drift to produce an appreciable effect, but there is the evidence of auroral effects as well as of magnetic storms to suggest that charged particles may be injected into the atmosphere with velocities comparable with that of light. These particles, if charged, will be deflected by the earth's magnetic field into the polar regions and will be given a West to East or East to West drift according to whether they are negatively or positively charged. It is very improbable, however, that such streams could reach the lower levels of the atmosphere, where the daylight layer is situated.

Again, the effect if it is present should increase very rapidly with the wave-length; now this is characteristic of the East and West effect which occurs at night, for it is only observed on wave-lengths greater than about 16 km and increases very rapidly on longer waves. We should therefore suggest that if this explanation is applicable to all it is only so in the case of night attenuation, and that unidirectional transmission cannot be produced by this cause in the daytime. The direction of the East and West effect which occurs at night suggests that the particles emitted by the sun at high speeds and caught up in the outer layers of the atmosphere are positively charged. The excessive attenuation suffered by the long waves from Bordeaux in the daytime may be an illustration of what may be called the "J. J. Thomson absorption" effect, but it is probably not unidirectional in this case.

In connection with long-wave absorption an experiment was carried out at Carnarvon which unfortunately had a negative result. Signals on a 40-km wave (100 amperes in the aerial) were sent out and listened for in Australia. Not a trace of them could be heard, even though the apparatus used had a fairly high degree of sensitivity. This again suggests excessive attenuations on these long waves.

Earth's Magnetic Field.

In view of the fact that the determining factor of wireless is the attenuation in the upper conducting

layer, and since this depends on the motion of the ions or electrons in the field of the wave, and since finally the motion of these is modified by the presence of a steady magnetic field, we should expect to find a relation between the transmission and the earth's magnetic field.

There are two effects which might be observed. The first is a rotation of the plane of polarization of the wave when transmitted along the magnetic field, and the second a difference of attenuation according to whether the waves are moving transverse to or along the earth's magnetic field. The rotation of the plane of polarization of a plane wave travelling through a medium containing free ions when a longitudinal magnetic force is superimposed is a well-known effect and has been described in various papers, books,* etc., so that the results of such investigations will be assumed.

The full effect of this variation will not be developed unless the mean free life of an ion, i.e. the interval between the collisions, is large compared with the time $T_0 = [m/(eH)]$. The effect is more likely to occur at high levels where the pressure is low, i.e. the mean free life of the ion large, than in the lower levels where it is small.

Accordingly we might expect some such effect in the night but not in the day when the lower layer comes into play.

If θ is the angle of the plane of polarization, then the maximum rate of rotation would be

$$\frac{\delta\theta}{\delta t} = \frac{e}{m}H = \frac{1}{T_0}\dagger$$

or

$$T_0\frac{\delta\theta}{\delta t} = 1$$

which with the value for H in the earth's magnetic field (roughly $0 \cdot 2$ C.G.S. unit) means a complete rotation every $0 \cdot 54$ km.

The evidence afforded by the observations on direction-finding suggests quite strongly that such an effect may exist at night but not in the day, hence we have further evidence that the day-reflecting layer is a region of greater pressure and is therefore lower than the night layer.

The free life, T, of an ion must be less than about 10^{-9} in order that the effect may not be observable in the daytime, so that the pressures at this height cannot be less than about 1/500th of the atmospheric pressure. That is, the height must be less than 35 km (approximately). The lower limit is probably higher than this if all the factors are taken into account.

The other effect shows up as a consequence of the increase of the resistivity of a medium containing free ions in a transverse magnetic field. Numerically the percentage increase in resistivity is *

$$\frac{\delta\rho}{\rho} = \frac{1}{12}\left(\frac{eH}{m}\right)^2 T^2$$

which can be expressed in terms of the time T_0 thus:—

$$\frac{\delta\rho}{\rho} = \frac{1}{12}\left(\frac{T}{T_0}\right)^2$$

which will therefore be a very small quantity unless T, the time between collisions, is large compared with T_0. As before, this effect is not likely to occur in daytime but may occur at night.

Conclusion.

It will be realized that in spite of the enormous amount of material already gained by the authors, due to the indefatigable work of Mr. Tremellen and his assistant Mr. Allnutt, there are still matters, e.g. East and West effect, seasonal and latitude variations, beat effect, etc., about which no decisive statements can be made, and we must look to the future to make good the observational data necessary. We must also leave to the future the framing of a complete theory of "World Transmission of Radio," for the explanations given in this paper must be looked upon rather as suggestions than as final and complete statements of the theory.

* See H. A. Lorentz: "Theory of Electrons."

† Correct value $\frac{eH}{m} \cdot \frac{1}{1+(2T_0/T)}$

* See O. W. Richardson: "Electron Theory of Matter."

Discussion before the Wireless Section, 6 May, 1925.

Admiral of the Fleet Sir H. B. Jackson: I think that the Institution and, in fact, all wireless engineers and wireless scientists, are very much indebted to the Marconi Company for arranging and financing the expedition, and especially to the authors of this paper for the work they did in making the observations and analysing the results. It is very difficult to say which is the most important part of the work that was done—the preliminary work of getting the apparatus designed, made and calibrated and put to very severe test to show that it was trustworthy, or the very hard work that was done by the observers during the tests, or the final analysis of the observations. I imagine that most of the discussion will be rather on the analysis of the results than on the actual work done in obtaining them. The authors have attacked the Austin-Cohen formula, which I think has had a long enough life, and they have analysed the results in detail so as to get the attenuation due to the different causes. The varying attenuations in different parts of the world comprise a new feature which is worthy of very serious study. The fact that the polar areas stop the waves is also of very great interest.

Mr. R. A. Watson Watt: I am particularly interested in the observations on atmospherics, and propose to confine my remarks to that section of the paper which deals with these observations. The convective origin of many atmospherics is now so well established as to justify the hypothesis that all atmospherics arise from convective processes in the atmosphere, and Mr. Tremellen's data form a valuable addition to the evidence supporting the hypothesis. In passing I may say that the wave-form observations of Appleton, Herd and myself confirm the authors' interpretation of the grinder as a series of clicks; this can be seen visually on the cathode-ray screen. The

authors, in differentiating between the click and the crash, refer the click to a single lightning flash, but this does not, of course, preclude a lightning origin for the crash, since sensibly continuous flashes of 5 seconds' duration can be observed visually in latitudes as high as 40° N. The authors indicate that the crash is a product of discontinuities similar to those whose passage forms the most important feature of the meteorology of Western Europe, and they have been fortunate in that their expeditions have taken them into regions where the general "world distribution" is shown up so beautifully as in Figs. 81 to 84, without being overlaid by meteorological phenomena which, although on a sufficiently large scale to affect the greater part of a continent, are still relatively local. In an examination of continuous records of the apparent direction of arrival of atmospherics in Great Britain and Egypt, on which (under the auspices of the Radio Research Board established under the Department of Scientific and Industrial Research) I was actually engaged when the present paper reached me, I was tracing a general "world distribution" following the sun, such as was to be expected from the general principle of convective origin, and which was bound to be traceable if the range of reception for atmospherics were sufficient, but which proves to be very frequently obscured in these latitudes by atmospherics associated with the passage of depressions. Of this a typical case was that of July 12 to 14, 1924, when, as reported elsewhere, a cold front was traced for some 2 000 km across Europe by our recorders. As a matter of history, the convective origin of atmospherics was, apart from direct correlations with observed lightning, shown by Sir Henry Jackson in 1902, and further evidence was collected by the British Association Committee in 1913–15; the solar control was shown by a very high correlation coefficient between apparent direction of arrival of atmospherics and solar altitude found by me in 1922 (in a series of observations which await full interpretation in the light of later observations, in which the complexities due to meteorological disturbances and to the radiogoniometric ambiguity have been reduced). In 1923 Eccles outlined a general distribution following the sun, and Schindelhauer, albeit in a very limited test-period of one month only, in March 1922 found a cum-solar swing of 17° range between 0800 and 1800 G.M.T. Our records show the general type of variation, in a test-period in May, to consist of a stream of atmospherics arriving from an Easterly point about 0900 G.M.T., with a slow swing to a South-Easterly direction of arrival at 1400, an accelerating swing through a Southerly direction at 1800 to South-West at midnight, and a comparatively steady direction of arrival from between South-West and West between midnight and 0800 G.M.T. This stream from the West dies out somewhat rapidly between 0800 and 1000 G.M.T., and is replaced by a new stream from the East. It is of interest to note that our records agree with those of the authors in placing the main source of atmospherics, between midnight and 0700 G.M.T., in South America, and in fact the addition of our mean direction of arrival for February to the 0300 chart of Fig. 85 gives a "three-bearing fix" from base lines of a length which few would have cared to adopt for radiogoniometric locations. It might be profitable to compare individual determinations, and I should be happy to exchange data with the authors if they think it worth while. I am glad to note that the authors agree with what I may now call the British, as opposed to the Continental, view of the average range of reception of atmospherics. I believe that the majority of our atmospherics come from distances over 1 000 km, and that the range of reception on ordinary long-wave sets is not less than the earth's semi-circumference, while, if I do not misinterpret their views, Bellescize, Bureau and others believe that the majority of atmospherics heard originate with a very few hundred kilometres of the receiver.

Dr. R. L. Smith-Rose: On page 936 it is stated that one difficulty in determining the effective heights of aerials is the lack of accurate knowledge of a transmission formula over semi-conducting earth. Whilst admitting the lack of experimental evidence on this point, I should like to suggest that it is sufficiently accurate to take the ordinary Hertzian formula in conjunction with an attenuation factor such as can be obtained from Zenneck's work and a knowledge of the conductivity of the earth. The latter quantity is known from recent measurements at wireless frequencies, and using the value obtained it can be shown that even on a wave-length so short as 450 m the attenuation is only of the order of 9 per cent for a distance of about 50 km. On long waves and the shorter distances involved in measuring effective heights the attenuation would thus appear to be practically negligible. This deduction from theory, however, does not obviate the necessity for some direct experimental evidence on the point. On page 939 it is stated that signals at Girvan are about $1\frac{1}{2}$ times as strong as at Broomfield. Whilst this is correct for N.B. and T., Marion (WSO) only gives 10 to 20 per cent increase in Table 3 and also Figs. 12 and 13. Is this due entirely to slightly shorter wave-length? In Figs. 17–30 ordinates are given in microvolts per metre, whereas in Figs. 31–59 the scale is E.M.F. in an aerial whose effective height is stated as 12 m. Is there any reason why the arithmetic was not completed in the last case while plotting the results? Although for the other transmitting stations the attenuation constant appears to be independent of the wave-length, Bordeaux gives a value of attenuation which is 30 to 50 per cent greater than the mean of that of the other stations for reception both in the Atlantic and the Pacific (see Tables 7 and 8). This is for the wave-length of 23·45 km, whereas when the wave-length was reduced to 18·8 km the attenuation constant was only 7 per cent above the mean for the other stations. This, taken with the report of the experiment tried at Carnarvon on 40 km, would appear to indicate that there is an upper limit to the wave-length which it is advantageous to use for long-distance transmission, this limit being in the neighbourhood of 18 km. Mention has been made of the lack of experimental knowledge of attenuation for overland transmission. For long-distance transmission a value of β, the

attenuation constant due to the land absorption, is obtained on page 983 as = 0·001, and is independent of wave-length. In col. 2 on page 982, however, the value of β is taken as 0·005 to calculate the ratios in Table 12 for the measurements at Broomfield and Girvan. Is this a mere printer's or clerical error or is there another explanation? On page 984, for the purpose of calculating the contribution of earth conduction loss to the attenuation, the resistivity of the earth is stated to fall between the limits of 10^{12} and 10^{13} electromagnetic units, which is from 10 to 100 times that of sea-water. I should like to ask how these values were obtained. The values of resistivity given in standard textbooks for the materials commonly found at or near the earth's surface, vary enormously and are mostly very much higher than the figures quoted. In some recent experiments carried out by Mr. Barfield and myself,* the effective conductivity of the earth was measured by a wireless method at 10 different sites in the South of England between Teddington and Land's End. The resistivities obtained varied from $1 \cdot 9 \times 10^{12}$ to $6 \cdot 4 \times 10^{13}$, and are thus in good agreement with those mentioned in the present paper. The results obtained were found to be fairly independent of the state of the surface of the ground—whether wet or dry, and the nature of the subsoil had no direct influence on the result when, as is usual, soil and vegetation existed at the surface. These values of the resistivity give an attenuation at short distances which is extremely small (only a few per cent) except on short wave-lengths, and, as shown in the present paper, its effect at distances of 3 000 km is only to reduce the strength of signals by 50 per cent. This I consider to be a very important result and it leads to a revision of our ideas as to the previously supposed bad effect of large tracts of land intervening between transmitter and receiver. Now, concerning the attenuation introduced by the earth losses on the waves, it is stated on page 984 that the wave can be pictured as being uniformly distributed between the upper and lower conductors. As mentioned above, calculation from the already known values of the earth's resistivity shows that the contribution of earth currents to the attenuation is negligible. On page 985, however, it is assumed that the energy of the wave passes at such a height from the ground that the introduction of an opaque screen near the earth makes no difference to the energy received at a point well beyond the screen. This would not appear to be quite compatible with the idea of uniform distribution of energy between the earth and the upper layer. Mention is made on pages 959 and 992 of the fact that the twilight line dividing light and darkness acts as a barrier to the passage of waves, examples being indicated in the diurnal variation curves. An excellent example of this effect was obtained on the occasion of the solar eclipse of January 24 last, when some measurements of signal strength were made at four separate stations in this country on some special transmissions from the Rocky Point station. The results obtained were described recently in the *Electrician*,† and the *Electrical Review*,* and were chiefly notable for a signal-strength time curve of the same characteristic shape at each observing station. A rise in signal strength during the eclipse was followed by a decrease to a well-defined minimum strength at a time which corresponded very closely to the passage of the shadow of totality across the great-circle path between transmitter and receiver. This is precisely similar to the effect of the twilight boundary mentioned in the paper. A possible explanation is that the waves passing from the dark to the light side will experience a certain amount of reflection except in the case of normal incidence on the boundary, which would only occur in certain rare circumstances. One side of the dark vertical "slot" in the atmosphere cut out by the eclipse would thus form a partial barrier to the passage of waves, particularly in the upper portions of the atmosphere. If this explanation is correct, one would expect to find that the minimum of signal intensity in the diurnal records of American signals observed in England would be much more marked when the sunrise boundary is passing across the Atlantic than in the corresponding sunset condition. I have not a sufficiently detailed knowledge of the usual occurrences of transatlantic measurements to say if this effect is at all noticeable. On page 976, and particularly on page 994, it is stated that various observations show without any sort of doubt that high-angle reflection is wholly absent in the daytime, and that the effect of reflection begins to be important at distances of about 700 km. I should like to ask for further details of the observations which have established such a point, for apart from the fact that the diffraction curve has departed from the observed values curve at a distance of 1 000 km, I have not come across details of these observations. The general impression I gathered from the paper was that very few, if any, measurements were made at distances below 1 000 km. A careful determination of this minimum distance transpires to be of great importance since it forms the basis of one of the methods of determining the height of the upper layer. In direction-finding several instances can be given of variations of bearings in daylight at much shorter distances than these. One of the most prominent examples is that of Leafield, which at a distance of 80 km has given variations ranging up to 16°. I have always understood that these variations are explained by means of reflected waves from the upper atmosphere and at such a range the angle of incidence must be comparatively small. On pages 994–996 calculations are given of the height of the upper layer. In the first method the above-mentioned minimum distance for reflection is employed to determine the limiting angle (θ in Fig. 114) within which the effective radiation takes place, and the relation obtained is that $d_0 = H/(2\theta_1)$. An arithmetical error seems to have occurred here, for, substituting $d_0 = 380$ and $\theta = 3°$, $H = 39 \cdot 8$, not 32·1 km as given in the paper. In the second method $d\sigma$ is taken as 400 at the top of page 996, whereas if the previously used value of 380 were taken H becomes 39·0, which is practically in complete agreement with the previous corrected

* *Proceedings of the Royal Society*, A, 1925, vol. 107, p. 587.
† 1925, vol. 94, p. 152.

* 1925, vol. 96, p. 214.

value. Now in regard to these calculations, the first is obtained from Watson's formula, which I think was derived on the assumption of a sharply defined reflecting surface, which would give high-angle reflection, as well as the low-angle cases used. The second method as represented by Fig. 115 appears to be a physical representation of the same mathematical problem. The formula employed is, however, derived on the assumption that the reflecting surface is very ill-defined and so high-angle reflection could not occur. It is surely surprising that two methods starting from such contradictory assumptions should give almost identical results for the height of the upper layer. It would also appear as if there is some coincidence in this agreement, since in the first case H is shown as proportional to d_0, which from Fig. 92 and page 982 appears to be approximately proportional to $1/\lambda$, whereas in the second case the final formula on page 996 gives H as independent of λ. Thus if other wave-lengths are used, two separate values of H would be obtained by the two methods. I have made these remarks on the more theoretical part of the paper not in any spirit of carping criticism, but rather to emphasize the limitation of the analysis by reason of the assumptions and approximations which have had to be made owing to the enormous lack of our existing knowledge on this subject. In spite of the magnitude of the experiments there are quite obviously many points and side-issues which must be left for further investigation, and I should like to ask the authors if, for the benefit of future workers who may have to tackle these problems, they would give any hints from their experience as to the most fruitful lines upon which a world-wide study of the propagation of waves might be carried out. It is quite within the bounds of possibility that at some future date an international body may organize such a world-wide research, and we should be proud that such an excellent start has been made by a group of workers in this country.

Mr. E. B. Moullin: This paper describes a wonderfully bold and complete piece of work. There must be many here who, like myself, have often wished to take part in such an expedition and may even have planned the details in imagination. The paper is full of information which is of immediate use in designing transmitting stations, and it contains a great deal of important data respecting the physics of the upper layers of the atmosphere which will be of great assistance to physicists studying these problems. I am particularly interested in the experiments to discover the appropriate value of the constant A_0 in the fundamental transmission formula and I think the information that it is sensibly equal to the theoretical value 120π is of great general importance. At one time the value 60π was often used in America: it seems certain that with a flat and resistanceless earth the correct value would be 120π, but in the presence of an imperfect earth it has seemed not unreasonable to take half this value. I have often wished for facilities to test this constant, because a lack of unanimity in the value used has led to a good deal of confusion in signal measurements. The point is now settled once and for all. It is worthy of notice that if the effective height of an aerial is measured by the Pession method, $h \propto 1/\sqrt{A_0}$, and therefore an error of 2 per cent in the value of A_0 makes only 1 per cent difference in the value deduced for h. With regard to the difficulty of deducing effective height by measuring the E.M.F. induced in a frame, I should like to know if the authors see any objection to the method I have used,* whereby the aerial itself is converted into a three-sided frame whose fourth side is formed by a wire running along, and in contact with, the ground. This method appears to me to remove the difficulty. I am surprised that the calculated values of effective height differ widely from the measured values and I think it would be of interest if we could be told some details of the calculations employed. The method of calculating the attenuation factor resulting from dielectric loss is very interesting. Experiments with well-insulated condensers appear to show that the energy loss per cycle is a constant fraction of the energy stored, as with magnetic hysteresis. This hypothesis has been used in an ingenious manner to deduce the form of the attenuation factor for wave transmission under a Heaviside layer. The discovery of zones in which beats are produced by the interference of the signals arriving by the longer and shorter paths is very interesting. I trust that the Marconi Company will experiment with a very steady station and then cause its frequency to vary in a harmonic manner and so be able to state definitely what is the cause of the phenomenon.

Mr. J. Hollingworth: It is not always appreciated how much preliminary care and consideration are required to obtain results such as those given in the paper, as work of this nature suffers from the severe limitation that, strictly speaking, no repetition of an experiment is possible, and everything has to be allowed for beforehand. The authors have also helped to remove a criticism which has been levelled against this subject, not altogether without justification, namely, that it was all theories and no facts. Personally I am particularly interested in it as I have been working on the subject for the past 18 months. I have for certain definite reasons restricted my measurements to distances not exceeding 1 500 km, so that I can offer no direct comparisons with the long-distance work, but certain general points are of special interest. The first is in connection with Fig. 14, showing the large change in intensity about the October–November period. I was not working during the years referred to in the figure, but last year exactly the same effect occurred not only on transatlantic stations but also at quite short distances and on all wave-lengths observed (minimum 9 000 m). Of course, at these short distances the effect is not always a fall in intensity; it is under certain conditions an equally abrupt rise, but in 1924 practically the whole effect was concentrated into two or three days (October 28–30). I do not know if the authors could determine from their figures whether the change was equally abrupt in previous years, but if so it appears that an almost world-wide watch kept over the period should be of great value. I gather that

* *Journal I.E.E.*, 1923, vol. 61, p. 72.

the authors' opinion of Bordeaux is that it is below normal on the 23 450 m wave and roughly normal on the 18 350 m wave. Dr. Austin, on the other hand, appears to hold the view that the long wave is normal and the short one unusually good, and his view is supported by the French observers. It also agrees with the results I have obtained from four different observing stations in the British Isles, where the signals are now 50–100 per cent greater than would be expected on the analogy of other stations with the same order of wave-length. I am in entire agreement with the statement that single observations should be treated with distrust, as I think the subject has been impeded by elaborate theories built on the results of a few observations at one station of one other station. On the subject of land attenuation I find some difficulty in accepting the authors' figures, at any rate for short distances. I gather that they consider the difference between the transatlantic signals at Girvan and Broomfield—a difference of about 50 per cent—to be due to the extra attenuation over 600 km of land. I think that this requires further verification not confined to these two stations and I should like to quote the following extract from my results. For the past 10 months I have had observations taken periodically of Leafield at Glasgow and Stavanger at Aberdeen. In each case the wave-length, aerial current and aerial heights are practically the same and the distances are respectively 477 km and 495 km, but the former is entirely over land and the latter entirely over sea. The results are averaged and plotted weekly, and in general they do not differ by more than about 5 per cent, though a few "freak" periods lasting about 3 weeks have occurred during which the difference is 100 per cent, after which they fall abruptly into coincidence again. I have not yet sufficient results to give a definite opinion on the height of the upper layer, but a rough approximation gives 50 km during the summer months, rising abruptly to about 65 km at the October change referred to above. I do not agree with the statement on page 994 that high-angle reflection is not present during the day, though certainly a rough calculation shows that the distances in the paper are too great for this phenomenon, which should rarely occur at distances greater than 1 000 km. Space does not permit me to develop the argument fully here, but as a typical example I may say that during the winter months the signals from Nantes at Manchester fall and at Aberdeen rise until at times the latter actually exceed the former although the distance is 60 per cent greater. This is only the most striking of a series of changes which are so systematic that it is impossible to ascribe them to local causes near any particular station.

Mr. R. H. Barfield: As one studies the paper one cannot fail to be struck with the number of directions in which important advances have been made. I think the chief are (1) the establishment of the fact that Watson's reflection formula is in agreement with experience; (2) the recasting of that formula into practical shape far superior to the Austin-Cohen formula; (3) the discovery of the "East-West" effect and of beat phenomena; and (4) the location of the places of origin of atmospherics in a most striking manner. On page 984 the authors distinguish between losses produced by the earth's resistivity, conduction losses in the vegetation, and dielectric losses. Now these are the factors which combine to produce the forward tilt of the wave-front, and the angle of this tilt is obviously a measure of the total losses produced by the surface. Dr. Smith-Rose has mentioned that we have recently made measurements of these forward inclinations at Slough and in many other parts of England, and though many of the measurements were made on surfaces covered with vegetation (e.g. long grass or small bushes) we find, from Zenneck's theory of tilts, that ground resistances in good agreement with the values given by the authors of the present paper are alone sufficient to account for the amount of tilt we obtained. This appears to me to be an experimental demonstration that the earth's resistance is the only appreciable factor in determining the amount of tilt of the wave-front of a horizontally travelling wave, and therefore is alone responsible for producing surface loss. This, of course, ignores the absorbing effect of trees which, being large compared with our apparatus, had to be avoided, but since even these are negligibly small in comparison with the length of waves dealt with in this paper, may not they be classified with smaller vegetation in estimating their probable effect? On page 994 the authors refer to "various observations which show, without any sort of doubt, that 'high-angle reflection' is wholly absent in the daytime." I should be very glad if they would indicate the nature of those experiments.

Prof. E. W. Marchant (*communicated*): Soon after the account given by Mr. Lunnon in the discussion on Mr. Elwell's paper on "Long-distance Wireless Transmission"* of the apparatus he had used for measuring signal strength, one of our research students, Mr. H. D. Sharpe, constructed, in the Laboratories of Applied Electricity, Liverpool, an apparatus similar to that described by Mr. Lunnon. I should like to confirm what the authors say as to the advantages of this method of measurement. We have made a great many tests in Liverpool, using galvanometer methods, and, although these are quite suitable for ranges up to 1 000 miles, the only method which has proved successful for estimating the strength of transatlantic signals has been the one which Mr. Lunnon described and which has been adopted in our later tests. A separate heterodyne circuit has been used in connection with the receiving circuit which not only greatly increases the signal strengths but also enables any very troublesome station to be made less troublesome by tuning the heterodyne circuit so as to make the disturbing station give a very low note. By this means measurements could be made with signals from very distant stations, even when near-by powerful stations were emitting signals of very nearly the same wave-length. In this latitude there is not, of course, the same difficulty with atmospherics that there is in tropical latitudes, and we have not had any serious trouble from them. I should, however, like to say a word or two about

* *Journal I.E.E.*, 1921, vol. 59, p. 677.

the arrangement used by Messrs. Lunnon and Tremellen, in which the "homodyne" signal has been switched on to the receiving aerial, instead of being sent through a dummy aerial circuit. In the process of making measurements we have found it necessary to compare the strength of the locally produced signal and the incoming signal at very frequent intervals. The procedure in making a measurement has been (1) to tune the circuit of the receiver for the signal that has to be measured until it is clearly heard on the telephones connected to our 7-valve amplifier; (2) having started the local oscillators by means of a change-over switch with mercury contacts, rapidly to change the connections from the signal which is coming in on the main aerial to the signal produced by the local oscillator in the dummy aerial circuit, and tune the circuit of the local oscillator until the pitch of the note heard from it is exactly the same as that of the received signal; and (3) to vary the mutual induction between the local oscillator and the receiving circuits until the two sounds are of exactly the same strength. The most troublesome operation is the tuning of the pitch of the signal from the local oscillator to that of the signals being measured, and to do this quickly it is necessary to change-over the mercury switch repeatedly. A great deal depends on the observer. Mr. Sharpe, who constructed the set and made the first measurements, was a good musician. He was able to adjust the local oscillating circuit very rapidly to give the same pitch note as that being produced by the incoming signal and, this having been done, the adjustment of the strength of the local oscillating current so as to make it exactly the same as the received signal was relatively easy. This, I think, was much easier for him to do than for other people with less keen musical ears. Mr. Arnold, who has continued the tests during the past 18 months, is also very quick at adjusting the tune of the local oscillating circuit correctly. I venture to think that it is very desirable that anyone using this method of test should have a good musical ear, and I think that such a person would be able to measure signal strengths, even when atmospheric disturbances and other stations are producing very considerable interference. Our tests have been made on the Annapolis time signals which are sent out at 4.55 (winter time). A Dutch station which comes in very often when the time signals are being measured has very nearly the same wave-length. We have found that by using the separate heterodyne circuit already mentioned and lowering the pitch of the note from the disturbing station, it is nearly always possible to get a fairly accurate measurement of the strength of the Annapolis time signal, when it is audible at all. Both Mr. Sharpe and Mr. Arnold have found that, with great care, they have been able to obtain consistent results on fairly loud signals, such as those from Nantes, within about ± 5 per cent. The order of accuracy of measurement diminishes for weaker signals, the variation in the measurements being about ± 10μV/m for a weak signal with a good operator. I should like to say a word on the measurement of the effective height of the aerial. The three-aerial method described on page 936 would seem to be a very good method of measuring the effective height of the aerial, provided the absorption along the path of the waves to stations A and B from C is similarly absorbent, but it is obvious that if the path from A to C is more absorbent than the path from B to C the measurement will not be exact. We had not the advantage of having three aerials available, and in order to determine approximately the effective height of our aerial we measured the strengths of the signals received from Nantes and Nauen. As particulars were available of the antenna currents and effective heights of the transmitting aerials at these two stations, we were able to estimate the effective height of our own aerial by the Austin-Cohen formula. Using this formula, the effective height, as determined by the average strength of the signal from Nantes, came to 2·3 m, which corresponded fairly closely to the actual height of the receiving antenna above the lead roof of the laboratory on which it was erected. The absorption term in the Austin-Cohen formula reduces the microvolts per metre by 36 per cent only, and, for determinations of the order of accuracy aimed at, the variations in the absorption would not be important. This result was checked by a measurement of the average strength of signal received from Nauen and the agreement was unexpectedly close, the values of the effective height agreeing within 5 per cent. As regards the measurements made on the two stations at Nantes and Nauen, the actual signal-strength variation from day to day is considerable. The extreme variation in the Nantes signals for the month of May, 1924, was from 1 800 to 710 μV/m with a mean value of 1 140 μV/m, the average variation being

TABLE A.

Strength of the Electric Field, E, in Microvolts per metre.

Date	Annapolis E
	μV/m
7 October	135
9 ,,	90
10 ,,	125
13 ,,	85
14 ,,	30
15 ,,	65
16 ,,	35
17 ,,	10
20 ,,	35
21 ,,	10
22 ,,	5
24 ,,	Inaudible
26 ,,	5
27 ,,	40
30 ,,	35
3 November	40

Mean value of E for the month of October = 50 μV/m.
Distance of transmission from Liverpool = 5 300 km.

± 25 per cent. Approximately the same ratio of variation was observed in the signals from Nauen. The measurements that have been made of the microvolts per metre from Annapolis, distant 5 300 km from Liverpool, show much greater variations. The results for October 1924 are shown in Table A. There have been many days since on which the Annapolis time signal has been inaudible. The effective height of the receiving aerial in Liverpool is, of course, small, and this has made the measurements more difficult than they would otherwise have been. A report on these measurements has been submitted to the British National Committee of Radio Telegraphy, and I am indebted to the Committee for allowing them to be mentioned in this discussion.

Messrs. L. Espenschied, C. N. Anderson and **A. Bailey** (*communicated*) : Upon the date the paper under discussion was read, there was given before the Institute of Radio Engineers in New York a paper reporting upon another long series of measurements of radio transmission upon the lower radio frequencies.* These latter measurements were made in the course of an experimental study of the possibilities of transatlantic radiotelephony across the North Atlantic which has continued for a period of over two years. We have, therefore, been particularly interested in the paper under discussion and in comparing certain of the measurements there given with the corresponding results obtained in the transatlantic radio-telephone measurements.

Diurnal signal characteristics.—We were impressed by the low night-time field strength of transatlantic transmission exhibited in Figs. 5, 6 and 7. We have found the normal condition to be one of *high* night-time fields, the values approaching as a maximum that defined by the inverse-distance law, with lower and more or less constant daylight field strength. Such of our measurements as do show low night-time values occur at times during which disturbances were in progress in the earth's magnetic field. Actually, the effect at such times is not merely to decrease night-time values but to increase slightly the daytime field. We have studied the data in regard to the earth's magnetic field for the dates corresponding to the figures mentioned and find not only that magnetic disturbances occurred during the period for which these measurements were taken, from May 13th to 23rd, 1921, but that they were unusually severe. It appears, therefore, that these curves display abnormal variations accompanying magnetic disturbances rather than typical diurnal variations.

Seasonal variation in daylight field strength.—Fig. 14 shows a very interesting effect in the reduction in the transatlantic daylight signal field which sets in during the late autumn months. This effect has also been observed in the transatlantic telephone measurements. The fact that for the time of year during which this increase in attenuation occurs, viz. the winter months, the transmission path lies quite close to the northern division line between the sunlit and the darkened hemispheres may be of significance in explaining this effect. It should be noted that there are other times during which the transmission path lies in or near the division line between the sunlit and darkened hemispheres, viz. those of sunrise and sunset, and during the night-time of the summer months. All of these cases appear to result in an increase in the attenuation.

Comparison of normal daylight transmission.—In general, a good agreement is found between those measurements for transatlantic transmission given in the paper and the corresponding measurements made in the transatlantic telephone study. In particular, our results agree quite closely with the measurements of Marion (WSO) for transmission across the North Atlantic given in Fig. 26. There is apparently some discrepancy between the data taken at the beginning of the trip on the S.S. "Dorset" and those taken at the end of the expedition on the S.S. "Boonah" (Fig. 24). It will be observed that the field strength received at 5 000 km on the S.S. "Dorset" (Fig. 26) was less than 50 μV/m, while for the same distance on the S.S. "Boonah" it was over 80 μV/m. Evidently part of this is due to the lower daylight values obtaining in the winter time. With respect to the measurements made upon Rocky Point's long-wave transmitter (WQL), as recorded in Fig. 71, we find that those of our measurements which were made at the time the S.S. "Boonah" was receiving WQL across the North Atlantic check very well with the results given. It should be noted, however, that the field strengths measured at this time were abnormally high, due to the fact that transmitter powers larger than normal were in use, the antenna current being approximately 1 000 amperes. The fact that the transmitter antenna current is known to have been changed during the period in which the measurements of Fig. 71 were taken emphasizes the necessity of adjusting the data to constant transmitter power before attempting to interpret them. It is of interest to compare certain of the measurement results given in the paper with those indicated by an empirical formula which expresses the measured results obtained in the North Atlantic radio telephone measurements. The constants of this formula, it will be understood, have been derived merely for the limited physical conditions of the United States–England transmission path and for the frequency range of 15 to 60 kilocycles. The formula is

$$E = \sqrt{(P_{\mathrm{kW}})}\frac{298 \times 10^3}{d}\epsilon^{-[0\cdot005d/\lambda^{1\cdot25}]}$$

In carrying out the transatlantic radio telephone measurements, the powers radiated from three of the stations reported upon in the paper have been determined by a series of comparatively local measurements in the direction of transmission. The radiated power corresponding to an antenna current of 600 amperes is in each case approximately as follows: WQL, 13 kW; WQK, 15·5 kW; and WSO, 9 kW. Using these primary data and substituting in the formula above, remarkably good agreement is found between these calculated values and the observed values, even to distances of 12 000–14 000 km. In the case of WQK (Fig. 24) and WSO (Fig. 26) this represents transmission not only West to East over the North Atlantic but also in the South-West direction when the S.S. "Dorset"

* L. Espenschied, C. N. Anderson and A. Bailey: "Transatlantic Radio Telephone Transmission," *Proceedings of the Institute of Radio Engineers*, 1926, vol. 14, no. 1. See *Bell System Technical Journal*, June, 1925; also *Electrician*, 1925, vol. 95, p. 175.

was in the South Pacific Ocean. Our North Atlantic data do not warrant any differentiation between East-West and West-East transmission. Such differences as have been obtained were within the error which could be attributed to incomplete data on radiated power or insufficient measurements of received field strength.

Source of static.—The paper presents valuable evidence indicating that the tropical belt, and in particular large land areas in it, may be regarded as major sources of atmospherics. The deductions which we have made from a study of the diurnal variations of atmospheric noise, exclusive of the high afternoon static which prevails during the summer months, have led to much the same conclusion. Of interest also, in the paper under discussion, is the apparent movement of the major source of static along with the 3 p.m. meridian. This is in conformity with meteorological data on thunderstorms which indicate that the hours of maximum occurrence of inland or Continental thunderstorms are in most places from 2 to 4 p.m. However, it appears that the time of maximum thunderstorms over the oceans is quite different, occurring between midnight and 4 a.m. The result of this may be to present to long-wave receiving stations in northern latitudes a more or less constant generation of atmospherics along the tropical belt and cause the major factor controlling the diurnal characteristic of atmospherics for a station located in England, for example, to be the transmission efficiency of the intervening medium. This is what is indicated by the analysis we have made of a long series of noise measurements in the transatlantic telephone experiments.

Messrs. H. J. Round, T L. Eckersley, K. Tremellen and **F. C. Lunnon** (*in reply*): Mr. Watson Watt has drawn attention to the divergence of opinion between English and Continental engineers as regards the source of X's, the latter considering that X's originate within a few hundred miles of the receiver. In contradiction of this and in support of the evidence in the paper that the source of X's is generally in the equatorial regions and may in many cases be thousands of kilometres from the receiver, we have some further evidence which was not included in the paper owing to want of space. Measurements made of the relative strength of X's by estimating the strength of signals necessary to read through them at 20 w.p.m., say, when plotted against the distance from the assumed source (obtained from directional measurements), give an attenuation curve of just the same type as that of a station situated at the source, and the presumption therefore is that our estimate of the source of X's is correct.

Dr. Smith-Rose has suggested that the appropriate transmission formula to use for short-distance work in the determination of effective heights is the Hertzian formula multiplied by a suitable ground attenuation factor such as can be obtained from Zenneck's work. We hardly think this is correct, in view of Sommerfeld's theory of the matter. It is shown by him that the Zenneck type of wave, i.e. a surface wave with its appropriate attenuation factor, does not develop its full intensity and is not important at distances which are small compared with the "numerical distance," a quantity defined on page 936. At distances small compared with this, such as are almost invariably used in determinations of effective height, the formula of the Hertzian type alone is appropriate. The difference is probably not of importance except from a theoretical point of view, for at these distances, i.e. at distances small compared with the "numerical distances," the attenuation factor is practically unity, and the difference between the two formulæ can be neglected.

With regard to the relative strengths of the American stations at Broomfield and at Girvan, the ratio of the strengths at Girvan to those at Broomfield is given as approximately $1\frac{1}{2}$. This refers to the average of all the stations received; Marion (WSO) with only 20 per cent difference is certainly anomalous. This anomaly was noted at the time, and a long series of measurements was made with the object of verifying the measurements and eliminating any possible local or temporal reductions in the signal strength at Girvan. This anomaly, however, persisted and is also reflected in the measurements made at Poldhu. The reason for this appears to be connected with the fact that signals do not die away quite uniformly with the distance, and that there is a slight sinusoidal fluctuation, which is shown up in Fig. 89. The nature of this fluctuation is different for different wave-lengths, with the result that over relatively short distances the signal from some stations, e.g. WSO, may appear to die away far less rapidly than those from others, e.g. WII and WGG.

Figs. 31 to 59, of which the ordinates are the actual microvolts, and not as in the case of the others the microvolts per metre, were originally plotted before the effective height comparison had been made. In order to save the labour of re-plotting, tracings were made of the originals in the expectation that they could be altered when the curves were reproduced for the paper, but this alteration was impossible in the limited time available.

The overland absorption factor is, as stated in the paper, a subject of a certain amount of uncertainty, which is perhaps reflected in the method of representing it. There is the choice of expressing the total absorption due to this cause in either the form $e^{-\gamma d}$ or $e^{-\beta d/\lambda}$, where β and γ are considered to be constants. On the whole the latter form is considered to be the more accurate.

The figures $\beta = 0 \cdot 005$ on page 982 and $\beta = 0 \cdot 001$ on page 983 are consistent in view of the variation of β with the distance, for the former refers to short-distance attenuation (600 km in the neighbourhood of the receiver) and the figure $0 \cdot 001$ to long-distance (approx. 9 000 km) transmission.

In the advance copies of the paper there was, unfortunately, an error in the designation of the ordinates of Fig. 94, which should read βd,* where β has the same significance as above, i.e. the total land absorption is $e^{-\beta d/\lambda}$, βd having the limiting value 12. Thus $e^{-\beta d}$ for wave-lengths of approximately 15 km is $e^{-0 \cdot 8} = 0 \cdot 449$, i.e. approximately $\frac{1}{2}$, as stated.

Earth resistivity.—The value of the earth resistivity used in the calculation of earth attenuation, which is of

* Corrected for the *Journal*.

the order of 2×10^{12} C.G.S. units and agrees with Dr. Smith-Rose's results rather than the commonly accepted textbook values which are much higher, was obtained in a variety of ways. The value was deduced primarily from the results of aerial resistance measurements. It is shown in a paper entitled "An Investigation of Transmitting Aerial Resistances" * that the proximity of the earth to a horizontal wire contributes an extra eddy-current resistance per cm of an amount

$$R_0 = \frac{\sqrt{2}}{h}\left(\frac{\rho p}{4\pi}\right)^{\frac{1}{2}} \times 10^{-9} \text{ ohms},$$

where ρ is the earth's resistivity, $p = 2\pi \times$ frequency, and h is the height of the wire above the surface of the earth. From the measurements made of various aerials and screens it was possible to deduce ρ, which is in all cases between 10^{12} and 10^{13} C.G.S. units. The value of ρ at Broomfield was also checked by measuring the high-frequency resistance between two buried plates. As a further check, some experiments to measure the tilt of the wave-front in the waves sent out from Clifden station during February, 1921, may be mentioned. The ratio of the horizontal to vertical electrical force was 1/97, whilst the calculated ratio (from Zenneck's formula) was 1/105, on the assumption that $\rho = 2 \times 10^{12}$ C.G.S. units. This therefore affords a good check on the value of ρ.

The idea that the energy sent out from a transmitter to a distant receiver may follow a path which rises to a considerable height above the earth's surface, like the trajectory of a shell, is not new in radio telegraphy nor is it inconsistent with the idea that the wave is distributed almost uniformly in the space between the earth and the Heaviside layer. With uniform distribution the wave surfaces are perpendicular to the surface of the earth. When, however, the rays follow the high trajectory the wave surfaces, which are perpendicular to the rays, differ only slightly from those in the uniform distribution, as shown in Fig. 97, and the density of energy flow is practically uniformly distributed across the wave surface. The rest of the argument follows from this hypothesis of slightly modified uniform distribution of energy flow.

Sunset effects.—The observed fact that the dividing line between light and darkness acts as a barrier to the long electric waves may, as suggested, be due to a reflection effect at this dividing line, but we are inclined to prefer another explanation. The amount of attenuation is a function of the resistivity of the upper conducting layer, and for the long waves with which this paper deals any increase of resistivity implies a corresponding increase of attenuation. Near the dividing line between light and darkness the sun's rays, which act as the ionizing agent in producing the conductivity of the lower or daylight layer, are removed and the ions rapidly re-combine, producing a consequent increase in the resistivity of the layer at this point, with a progressively increasing local attenuation. This attenuation, however, does not increase indefinitely with the resistivity of the lower layer, for with infinite resistivity the lower layer disappears and brings into play the night layer with its appropriate attenuation. Thus we should expect a transient increase in the local absorption during the transient re-combining period. There are two observed facts which tend to confirm this theory. The first is the observed variation of the time of sunset dip with wave-length, and the second is the absence of sunset or sunrise minimum on short waves of the order of 100 m. With regard to the former observation, it should be observed that the local attenuation referred to is a function of (ρ/λ), so that, as ρ increases, the value of ρ/λ reaches its critical value (for maximum absorption) sooner for short wave-lengths than for long ones, thus ensuring a progressive delay in the occurrence of the sunset minimum as the wave-length increases, which is in accordance with the observations. Again, on sufficiently short waves the attenuation on practically any theory is a function of (ρ/λ), so that if we consider the region where the attenuation decreases with increasing frequency (e.g. between 30 and 100 m) the attenuation must also decrease with increasing resistivity and there is a gradual increase of signal strength from the day to the night value as the twilight band passes between the two stations. The absence of high-angle reflection can be inferred partly from the usual absence of interference effects and directional distortions and partly from the results of observations with the "heart shaped" directional receiver. In the latter case the balance between the current induced in the vertical aerial and that in the frame would not be preserved if there were any high-angle reflection. This does not preclude the possibility of occasions when high-angle reflections may be present even in the daytime, especially in the winter time in high latitudes where conditions approximate to those which obtain at night, but the rarity of these effects suggests that high-angle reflection in daytime is the exception rather than the rule.

The estimate of the distance at which reflection begins to play an important part in the daytime was made by a comparison of the observed attenuation curves and the diffraction curves. The actual attenuation curves have in some cases been extrapolated backwards a little. The figure 700 km is very approximate; all one can say is that 400 km is too small and 1 000 km is too much. Too much stress, therefore, must not be laid on this figure. In using this figure for determining the height of the layer only approximate results were aimed at, and the assumptions which formed a basis for the calculation are also only approximations to the truth. Of the two methods for computing this height the latter (on page 996) should be considered as much more accurate. The two methods are not, in our opinion, contradictory, nor do they even differ to any great extent. Both methods involve the assumption that the layer is ill-defined, so that reflection is confined to practically glancing incidence; the former, however, assumes further that the energy within a cone of angle θ, where θ is so chosen that the reflected ray comes down at 700 km distance, is uniformly distributed over the space between the earth and the Heaviside layer. To emphasize the fact that

* *Journal I.E.E.*, 1922, vol. 60, p. 581.

the assumption of an ill-defined layer is involved in this calculation, we would draw attention to the statement at the top of the first column on page 995, where it is stated that "in view of the fact that high-angle reflection is absent, let us suppose that the energy radiated within a cone of angle θ (see Fig. 87) is reflected, but that higher-angle transmission than this is absorbed or, anyhow, not reflected," which is a direct consequence of the assumption of an ill-defined layer. The two methods would be in exact agreement if instead of assuming that θ was a constant for all wave-lengths, i.e. that the distance at which reflection becomes appreciable is also independent of λ, we assumed that $\theta = H/8\lambda$, an assumption which, in view of the indefinite nature of this distance, is perfectly justifiable. By reversing the process we may use the second formula to determine θ and so find that higher-angle reflection than about 3° on a 15-km wave-length is absent, confirming our previous estimate that high-angle reflection is in general absent in the daytime.

It was hoped that the paper itself would suggest the lines of future research; one obvious requirement is the extension of the work to shorter wave-lengths. The region below 5 000 m has not been studied with any degree of thoroughness, and we have theoretical evidence that a change in the nature of daylight transmission occurs about this wave-length and a further change on ranges from 50 m downward *; an investigation of field strengths on these wave-lengths would therefore be of the greatest value.

In reply to Mr. Moullin, the method of using a frame with a wire running along the earth as the fourth side for the absolute determination of effective height should not, we think, be open to any objection unless the difficulty of measuring the current at a symmetrical point be serious. Thus it is usually necessary to ensure symmetry by measuring the current at the centre of the lower wire of the frame. This, we think, would be impossible in Mr. Moullin's case, but the necessity for symmetry is very much reduced in this case and we doubt if it is a serious point. The method of calculating the effective heights was one in which the distribution of the current in the aerial was assumed to be sinusoidal with a node at the end of the aerial wire; the effective height was then determined from the relation

$$\text{Effective height, } h = \frac{1}{EI_0}\int Eidh$$

where E was assumed to be the electric force (asssumed independent of h), I_0 the current at the base of the aerial, and i the current at any point h in the aerial. With the ever-increasing interest in short waves we are afraid that it may be a long time before we are able to test whether the beats observed in the neighbourhood of the antipodes are due to a variation in the frequency of the transmitter or whether they must be attributed to one of the other causes suggested in the paper.

In reply to Mr. Hollingworth the sudden change in the received intensity at the end of October or beginning of November was originally noticed in the Clifden–Glace Bay services. This period during which it was practically impossible to get signals, was noticed regularly every year; the dates on which the most intense reduction were observed were in the neighbourhood of November 13th. There is a similar weak period, but not quite so marked, in the Ongar–Glace Bay service (GB, $\lambda = 7\,800$) at about a symmetrical time in the early part of the year, i.e. about the beginning of March, which may perhaps be attributed to the same cause, whatever it may be.

All our measurements show an abnormally high attenuation on Bordeaux's longer wave, to an extent we should consider outside the limits of experimental error, and indicate that the 18·35 km wave is normal. This, of course, depends on how one defines "normal" transmission. On the basis used throughout the paper, however, the long wave is certainly the abnormal one.

The estimate of land absorption based on the relative strengths of signals from a given station at two ranges, one of which includes more land than the other, should, we think, bear more weight than one which involves the use of two different and differently situated stations each, as were used by Mr. Hollingworth. The former estimate is freed from any assumption as regards the effective radiation from the given station or stations, whereas the latter is not. Moreover, the estimate in the particular case referred to does not rest on the basis of the observations of two stations only, but has the additional evidence of the measurements made on Clifden, Glace Bay and Rocky Point (WQK), the latter two being measured at Poldhu and Broomfield simultaneously, the ray to Poldhu being also practically wholly over sea.

In the case of GB signals the difference was very marked indeed, the signals at Poldhu being as much as 3·8 times stronger than those received simultaneously at Broomfield. The atmospheric absorption should in this case only account for an increase of 1·4 times the signal strength. The case for a very considerable reduction due to land absorption is, we consider, quite strong.

Mr. Hollingworth does not indicate how he arrives at his estimate of the height of the daylight reflecting layer, but we agree with him that there is apparently evidence of an increase of height in the winter time, although our estimate of the change is not so great as his. The reply to Mr. Hollingworth's criticism with regard to daylight interference effects is, we think, contained in our reply to Dr. Smith-Rose.

The point raised by Mr. Barfield is a little difficult to discuss in view of our present ignorance of the mechanism of dielectric loss. The experiments on this loss made in connection with the investigation of transmitting aerial resistances showed clearly that it was the *vertical* electric force which was responsible for this loss, and suggests that the energy in this case was transmitted practically horizontally over the earth's surface to the place where it is lost. With regard to the transmission losses in big structures on the earth's surface, the same argument would apply. The observations of the tilt of the wave-front over grassy surfaces would suggest that the loss under such

* See *Nature*, 1925, vol. 116, p. 924.

conditions is purely resistive, and the dielectric loss, if it is present, should be attributed to the larger structures such as trees, bushes, houses, etc. The question with regard to high-angle reflection has already been dealt with.

In reply to Messrs. Espenschied, Anderson and Bailey, who raised the question of diurnal signal characteristics, with regard to the contrast between day and night signals it must be remembered that the results obtained by us across the Atlantic refer to very much longer waves than those employed in the transatlantic telephony experiments, where the difference between day and night values are much greater. It should be noted that the particular results referred to are rather in the nature of exceptions and that over very great distances the attenuation constant at night appears to be approximately one-half the day-time value in the range of wave-lengths 6–25 km (see page 987). It is interesting to note the apparent connection with disturbance of the earth's magnetic field, but a large amount of material is necessary before a correlation between the disturbance of the earth's magnetic field and the attenuation of radio signals can be established definitely.

Comparison of normal daylight transmission.—It is satisfactory to note the agreement between the measurements made by two different measuring instruments. It might be well to correct the impression which might be suggested by the comments of Messrs. Espenschied, Anderson and Bailey, viz. that we have neglected to take account of variations in transmitted power. There are, no doubt, some cases where the necessary information was not forthcoming, but all the results obtained on the S.S. "Dorset" were, by the courtesy of the Radio Corporation of America, who gave us copies of the transmitting logs, reduced to constant transmitting current. Similar reductions to constant transmitting current were made in the case of Carnarvon, Clifden and Glace Bay, and the agreement of the results obtained from these with those obtained from other stations suggests that the effect of variations of transmitted energy from the latter cannot have been of very great importance when averaged over the long period of reception.

The variations of the transmitted power from the American stations during the return voyage on the S.S. "Boonah" may account for the rather wide scattering of the values of α obtained. The empirical formula developed by Messrs. Espenschied, Anderson and Bailey is certainly in good agreement with the results obtained, but, as stated in the paper, it has the disadvantage of being purely empirical, so that very little information can be gleaned from the fact that the falling-off of signal strength can be expressed in this manner. There are probably a large number of different empirical formulæ which would agree with the observations with the same degree of accuracy, so that too much stress must not be laid on any particular one.

THE REVERSED-ROTATION SHORT-CIRCUIT TEMPERATURE-RISE OF INDUCTION MOTORS.*

By J. H. R. NIXON, Associate Member.

(*Paper first received* 1*st January, and in final form* 7*th May*, 1925.)

SUMMARY.

The paper analyses a method of testing induction motors for temperature-rise, used mainly when means of loading are not available.

It is shown that the results of such tests are of the greatest value when studied in conjunction with certain design features of the machines, and simple expressions are developed which enable the test-measurements of heating to be converted to probable values of full-load temperature-rise.

The conclusions reached are compared with the results of actual tests.

The problem of obtaining and dissipating large quantities of energy renders the full-load temperature testing of large machines at makers' works an undertaking of great practical difficulty, and recourse has generally to be made to some form of equivalent heat test by which the losses of the machines are simulated without undue expenditure of energy. It is seldom, however, that such equivalent tests produce direct indications of the normal heating under full-load conditions, and the results must be appreciated with regard to the nature and distribution of the losses in addition to the manner of cooling, in order to obtain a true estimate of their meaning. The paper is an attempt to show how the results of an equivalent test applied to induction motors may be interpreted, by simple and practical methods, into reasonable indications of full-load temperature-rise.

The test, known as the "reversed-rotation short-circuit test," is made by driving the rotor at normal full-load speed in opposition to the direction of the rotating field due to the magnetizing current in the primary windings, that is, in the opposite direction to that in which it would tend to run normally. The secondary windings, which are usually on the rotor, are short-circuited and a supply voltage, of the same periodicity and number of phases as that for which the primary windings are designed, is impressed upon the stator windings (assuming they are primary), and the voltage is adjusted to a value which will circulate full-load current in these windings. The machine is run under these conditions until the temperatures are steady, when observations of the temperature-rise are carried out in the usual way. It is evident that since the rotor is running at its normal speed, the conditions of ventilation in the machine will be the same as are present in service, provided the normal air supply is available for the test, which, with the exception of special cases, should present no difficulty. Furthermore, it follows that the rotational losses due to windage and friction will not differ greatly from the values obtained in service.

The remaining losses which appear in the form of heat are :—

(1) Stator copper loss ;
(2) Stator iron (or core) loss ;
(3) Rotor copper loss ;
(4) Rotor iron (or core) loss ;

and these will be considered in separate relationship to their full-load values.

(1) *Stator copper loss.*—This is made up of I^2R and eddy-current losses, each dependent upon the current circulating in the stator windings. Since this current is adjusted to its full-load value, the loss in the copper during the test is equal to the loss at full load.

(2) *Stator iron loss.*—The rotor windings are short-circuited and consequently a comparatively low voltage is required at the stator terminals to circulate full-load current in the stator windings. In fact this voltage corresponds to the impedance voltage of the machine.

Let E_{ph} = the normal pressure per phase for which the stator windings are designed.
Z' = the total equivalent impedance (stator and rotor) per phase.
I_{fl} = the normal full-load stator current per phase.
K = a constant.

Then, with short-circuited secondary

$$\frac{E_{ph}}{Z'} = KI_{fl}$$

whence

$$I_{fl}Z' = \frac{E_{ph}}{K}$$

Now by the well-known fundamental relationship of voltage and magnetic flux

$$E = 4 \cdot 44 K_1 f_1 T_2 \Phi \times 10^{-8}$$

That is, in a given machine and at normal frequency $E = K_2\Phi$, where K_2 is a constant.

Hence the main flux Φ and consequently the magnetic densities due to the main flux are directly proportional to the applied voltage E. In the test the applied voltage is E_{ph}/K; therefore the main flux is equal to

* Thesis accepted in lieu of the Associate Membership Examination.

Φ/K and the magnetic density due to this flux is equal to B/K, where B is the normal density due to Φ.

Now the iron loss is made up of hysteresis and eddy-current losses, and varies with the magnetic density in accordance with well-known laws as follows:—

Hysteresis loss varies as $B^{1\cdot 6}$.
Eddy-current loss varies as B^2.

From this, the iron losses in the stator core and teeth due to hysteresis and eddy currents under the conditions of this test may be written, relatively to the losses at full load, as $(1/K)^{1\cdot 6}$ and $(1/K)^2$ respectively.

The value of K for an average machine is 5, and taking this value as an example the above ratios are $1/13\cdot 2$ for hysteresis losses and $1/25$ for eddy-current losses, from which it is evident that the iron loss in the stator is small enough to be neglected from the point of view of its influence upon the temperature-rise.

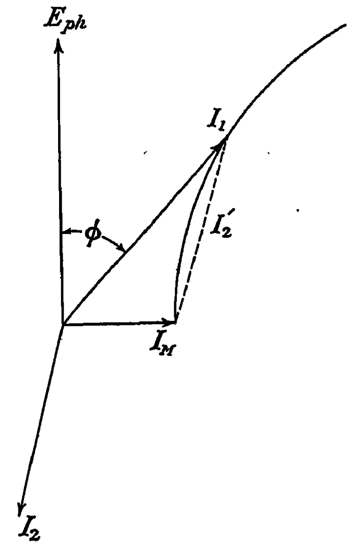


FIG. 1.—Stator and rotor currents at full load.

In addition to the above-mentioned loss a certain amount of iron loss is produced in the stator teeth by stray flux due to current flowing through the windings. This loss is not easy to calculate and, from the point of view of heating, may be neglected, particularly as it is also present at full load.

(3) *Rotor copper loss.*—The losses in the rotor copper exceed the losses at full load for the following reasons:—

(*a*) The current in the rotor (secondary) windings is, by reason of the windings being short-circuited, greater than full-load current.

(*b*) Eddy currents exist in the copper which are not present at full load.

(*c*) Following upon the increased loss and the consequently increased temperature, the final resistance of the windings is higher.

These effects will be discussed in detail, as they constitute a predominating factor in the results obtained.

(*a*) The relationships between stator and rotor currents are made clear by Figs. 1 and 2 which are drawn to the same scale, the stator current I_1 having the same value in each case. Now the resulting magnetizing effect of the stator and rotor currents I_1 and I_2 is equal to the magnetizing effect of the current I_M. Under the conditions of test, I_M is negligible and the magnetomotive force of the rotor current may be regarded as equal and opposite to the magnetomotive force of the stator current, that is to say, $I_1 = I_2'$, where I_2' denotes the rotor current in terms of the stator winding.

If $\cos\phi$ is the full-load power factor of the motor, and I_M is assumed to be 90 degrees out of phase with E_{ph}, then, by the geometry of Fig. 1,

$$I_2'^2 = I_1^2 + I_M^2 - 2I_1I_M\cos(90-\phi)$$

Let $I_M = K_3I_1$, where K_3 is a constant,

then $$I_2'^2 = I_1^2 + K_3^2I_1^2 - 2K_3I_1^2\sin\phi$$

i.e. $$I_2'^2 = I_1^2(1 + K_3^2 - 2K_3\sin\phi)$$

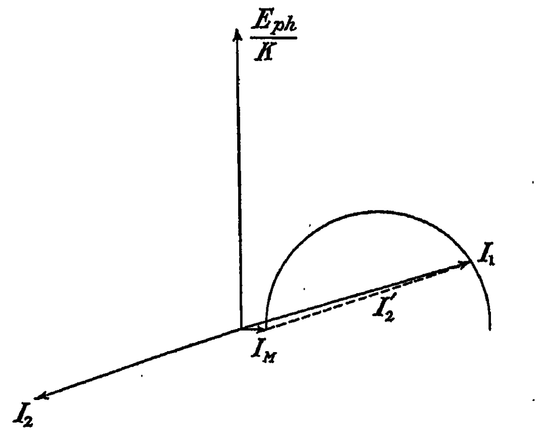


FIG. 2.—Stator and rotor currents at short-circuit.

Now in the test $I_2' = I_1$, hence the ratio of rotor current to its value at full load is

$$\frac{I_1}{I_2'} = \frac{I_1}{I_1\sqrt{(1+K_3^2-2K_3\sin\phi)}} = \frac{1}{\sqrt{(1+K_3^2-2K_3\sin\phi)}}$$

and, since the loss is proportional to the square of the current, the increase in rotor copper loss from this source is in the ratio

$$\frac{1}{1+K_3^2-2K_3\sin\phi} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

It may be noted in passing that this ratio is approximated to very closely by the expression $(1/\cos\phi)^2$, but the latter is likely to give incorrect results if used indiscriminately.

(*b*) *Loss due to eddy currents.*—When the motor is developing its full-load torque at its natural speed, the slip is small and therefore the frequency of the induced current in the rotor windings is low; but in the test the rotor is driven at full speed in opposition

to the rotating field of the stator, hence the frequency of the induced current is practically double that of the supply frequency, and, whereas at full load the eddy currents in the rotor copper produce a loss which is negligible, the loss at double the line frequency is likely to be formidable. The loss from this source may be calculated readily from the curves due to A. B. Field.

(c) *Loss due to increased resistance.*—To take this loss into account is probably a refinement which is hardly justified in view of the approximations necessarily involved in a test of this nature, but it can be so quickly estimated that there is little or nothing to be gained by ignoring the extra loss involved. According to B.S.S. No. 72 of 1917, the temperature coefficient of the change of resistance of copper is to be deduced from the formula

$$\frac{1}{234 \cdot 5 + t_0}$$

where t_0 is the initial temperature of the winding in degrees C.

Then if R_t = the final resistance,
R_0 = the initial resistance at t_0 °C., and
t = the temperature-rise in degrees C.,

$$R_t = R_0\left(1 + \frac{t}{234 \cdot 5 + t_0}\right)$$

i.e.
$$\frac{R_t}{R_0} = 1 + \frac{t}{234 \cdot 5 + t_0}$$

This equation can be conveniently expressed in the form of a chart (Fig. 3) which enables the increase in resistance for a given temperature-rise to be read at a glance.

For example:—*It is required to find the increase in resistance of copper the temperature of which has been raised by 26 deg. C. from an initial temperature of 25° C.*

Read horizontally from the ordinate at 25° C. to the point of intersection with the lower curve, and from this point proceed vertically to the given temperature-rise on the inclined scale. The point thus found is the ordinate of resistance increase, which may be read directly from the appropriate scale by horizontal projection. The result in the example is 1·1, i.e. 10 per cent increase in resistance above that measured at the initial temperature.

(4) *Rotor iron loss.*—The losses in the rotor at full load are inappreciable, but they become of greater magnitude when the rotor is run as in the test. Although the main flux does not link with the rotor, the leakage flux due to the rotor current threads mainly the rotor teeth and is of double the line frequency, consequently the ensuing loss is not inconsiderable. Unlike the corresponding loss in the stator teeth this is not present at full load, due partly to the different value of the current but mainly to the great difference in frequency of this stray flux between normal slip frequency and that of reverse rotation. However, this iron loss is exceedingly complex and difficult to calculate accurately. For practical purposes it may be assumed to be equivalent to the loss in the teeth at 20 to 25 per cent of normal density calculated at a frequency which is double that of the supply. The lower percentage is applicable to machines having few poles, and increases slightly with the number of poles.

Influence of the Rotor Losses upon Stator Temperature.

From the foregoing considerations it would be expected that the temperature measurements made on this test would show the average rotor temperature-rise to be higher than at full load, and the average stator temperature-rise to be lower. This would be true of a machine having pure axial ventilation and with the air paths so disposed that air which has cooled the rotor does not influence the temperature of the stator. However, the most common arrangement is that which takes advantage of the natural draught of the rotor and results in a combination of radial and axial ventilation in which a large proportion, if not all, of the air which cools the stator first passes through or by the rotor. The extent to which this occurs will influence the temperature-rise of the stator over and above that due to its losses alone.

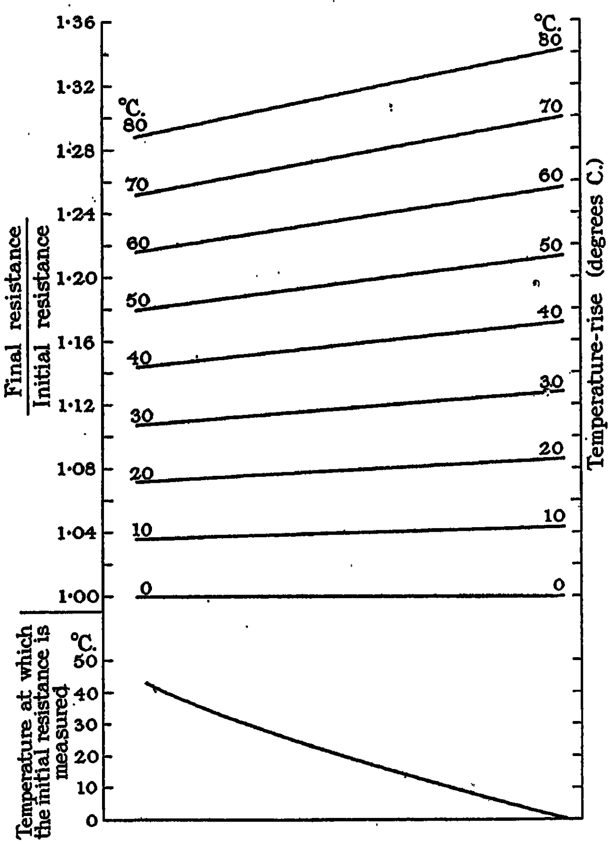


FIG. 3.—Temperature-rise by resistance.

It is therefore important to have an approximation of the proportion of stator cooling air which has received heat from the rotor prior to entering the stator, in order to estimate the effect of the rotor excess losses upon the

heating of the stator. Suppose, for example, that the whole of the stator cooling-air first passes through the rotor, then at full load the air entering the stator is raised in temperature by an amount proportional to the full-load losses occurring in the rotor. Now on the short-circuit test this is raised by a further amount on account of the extra losses in the rotor, and the temperature-rise above atmospheric temperature of the stator carrying the same loss under each condition would be higher on short-circuit by that amount.

Let T_0 = temperature of the atmosphere surrounding the machine under test.
T_1 = temperature of the air leaving the rotor at full load.
V = proportion of stator cooling-air which has received heat from the rotor.

Let it be assumed that the temperature of the air passing the rotor is raised in proportion to the losses carried by the rotor.

Then at full load the temperature of the air entering the stator is

$$VT_1 + (1 - V)T_0$$

If W_{2fl} = rotor loss at full load and W_{2sc} = rotor loss at short-circuit, the temperature of the air leaving the rotor at short-circuit is

$$\frac{W_{2sc}}{W_{2fl}}T_1$$

and the temperature of the air entering the stator is

$$V\frac{W_{2sc}}{W_{2fl}}T_1 + (1 - V)T_0$$

The primary concern is the amount by which the temperature of the air entering the stator at short-circuit exceeds that at full load, as this may be regarded as a definite addition to the temperature-rise of the stator.

Increase of temperature

$$= \left[V\frac{W_{2sc}}{W_{2fl}}T_1 + (1 - V)T_0\right] - [VT_1 + (1 - V)T_0]$$

$$= V\frac{W_{2sc}}{W_{2fl}}T_1 - VT_1$$

$$= VT_1\left(\frac{W_{2sc}}{W_{2fl}} - 1\right)$$

Now since T_1 depends for its actual value upon W_{2fl}

$$T_1 = K_4 W_{2fl}$$

where K_4 is a constant, and, by substitution, the increase of temperature

$$= V(K_4 W_{2fl})\left(\frac{W_{2sc}}{W_{2fl}} - 1\right)$$

$$= VK_4(W_{2sc} - W_{2fl})$$

That is to say, the temperature-rise is proportional to $V(W_{2sc} - W_{2fl})$ and the loss obtained by this expression will have the same effect upon the stator temperature-rise above atmosphere as though it occurred in the stator itself. It may therefore be assumed to be located in the stator and form an artificial part of the stator losses.

Effect of the Separate Losses upon the Temperature-Rise of the Stator.

If the copper were so insulated from the iron that no flow of heat could take place between copper and iron, or vice versa, the temperature-rise of each element would be proportional to its own losses, independently of the other. Thus, with no iron loss and full copper loss, whilst the copper would reach its normal temperature-rise, the iron would not rise above the temperature of the air passing by it. In practice, an exchange of heat does take place between copper and iron, according to the type of insulation used, and this insulation may be broadly divided into two classes, viz. that used for low-tension and for high-tension windings. The ordinary insulation adopted for low-tension windings offers but little resistance to the flow of heat, and this naturally results in fairly even temperatures throughout the stator, whatever the distribution of the losses. If W_{fe} and W_{cu} denote the core loss and copper loss respectively in a low-tension stator, the temperature-rise measured at any part of the stator may be regarded as proportional to $(W_{fe} + W_{cu})$.

Now on short-circuit with reversed rotation the value of W_{fe} is negligible, and it has been assumed that the stator carries a loss equal to $V(W_{2sc} - W_{2fl})$.

Hence if t_s = the temperature-rise of the stator on short-circuit and t_f = the temperature-rise of the stator on full load

$$\frac{t_f}{t_s} = \frac{W_{cu} + W_{fe}}{V(W_{2sc} - W_{2fl}) + W_{cu}}$$

and the probable value of

$$t_f = t_s\left[\frac{W_{cu} + W_{fe}}{V(W_{2sc} - W_{2fl}) + W_{cu}}\right] \quad . \quad . \quad (2)$$

The type of insulation used for high-tension windings affords a somewhat more special problem, for the thickness of the insulation between copper and iron is such that a considerable heat gradient may exist, and the probable temperature-rise at full load needs to be estimated in a slightly different way.

Let t_{cu} = temperature-rise of the copper at short-circuit (measured on the end windings).
t_{sfe} = temperature-rise of the core at short-circuit.
t_{ffe} = temperature-rise of the core at full load.
t_1 = temperature-rise of the cooling air above normal.

Now the iron core is receiving heat from the cooling air (preheated by the rotor) and from the stator copper.

Temperature-rise of iron due to copper loss in winding $= t_{sfe} - t_1$.

Now in watts, say, this is equivalent to $\frac{t_{sfe} - t_1}{t_{cu}}W_{cu}$.

Then the iron temperature-rise at full load relatively to the temperature-rise at short-circuit

$$= \frac{t_{ffe}}{t_{sfe}} = \frac{W_{fe}}{[(t_{sfe} - t_1)/t_{cu}]\,W_{cu}}$$

and

$$t_{ffe} = \frac{W_{fe} \times t_{sfe}}{[(t_{sfe} - t_1)/t_{cu}]\,W_{cu}} \quad . \quad . \quad . \quad (3)$$

The temperature-rise of the copper at full load would be

$$t_{ffe} + (t_{cu} - t_{sfe}) \quad . \quad . \quad . \quad . \quad . \quad (4)$$

525-volt 50-cycle three-phase circuit, and the average temperatures observed were as follows :—

After 6 hours at full load :—

Stator	56·5° C.	Rise = 38·5 deg. C.
Rotor	37·0° C.	Rise = 19·0 deg. C.
Room	18·0° C.	

After 6 hours at reversed-rotation short-circuit :—

Stator	55·0° C.	Rise = 36·0 deg. C.
Rotor	54·0° C.	Rise = 35·0 deg. C.
Room	19·0° C.	

TABLE.

Brake horse-power	150	250
Speed, in r.p.m.	485	225
Voltage	440	400
Frequency, in cycles per sec.	50	50
No. of phases	3	3
Full-load stator copper loss, watts	3 610	7 140
Full-load stator iron loss, watts	4 330	4 350
Full-load rotor copper loss at room temperature, watts	2 600	3 900
Estimated full-load power factor	0·87	0·77
Steady temperature-rise after reversed-rotation short-circuit run with full-load stator current—		
Stator	31 deg. C.	56·5 deg. C.
Rotor	40 deg. C.	54·0 deg. C.
Temperature of surrounding air	17° C.	20·0° C.
Multiplying factors for excess rotor loss—		
By excess current	1·33	1·61
By eddy current	1·44	1·73
By resistance	1·16	1·213
Total rotor copper loss, watts	5 770	13 200
Iron loss in rotor teeth, watts	420	580
Total rotor loss in test, watts	6 190	13 780
Full-load rotor loss, watts	2 780	4 150
Calculated full-load temperature-rise of rotor (by Equation 5)	18 deg. C.	16 deg. C.
Calculated full-load temperature-rise of stator (by Equation 2) [$V = 1$]	35 deg. C.	39 deg. C.
Measured full-load temperature-rise of rotor	17 deg. C.*	19 deg. C.
Measured full-load temperature-rise of stator	31 deg. C.*	40 deg. C.
Temperature of surrounding air	18° C.	21° C.

* Measured after a run in which the load averaged 95 per cent of full load.

TEMPERATURE-RISE OF THE ROTOR.

This may be simply deduced from the ratio of the losses at short-circuit to those at full load in proportion to the short-circuit temperature-rise. Let this latter be t_{2sc}. Thus the probable full-load temperature-rise is

$$t_{2sc}\frac{W_{2fl}}{W_{2sc}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

APPLICATION OF THE METHOD TO AN ACTUAL CASE.

Heating tests were carried out upon a 100-b.h.p. induction motor designed to run at 720 r.p.m. on a

The following data are deduced from no-load and locked-rotor short-circuit readings in addition to resistance measurements :—

Magnetizing current at normal pressure	40 amps.
Full-load stator current per phase	106 amps.
Full-load stator copper loss	2 720 watts
Full-load stator iron loss	2 710 watts
Estimated full-load power factor	0·85
Full-load rotor copper loss	2 030 watts at 19° C.

ROTOR LOSSES ON SHORT-CIRCUIT.

(*a*) Increase above full-load copper loss by excess current (by Equation 1) :—

$$\left(K_3 = \frac{40}{106} = 0 \cdot 378\right)$$

$$\frac{1}{1 + 0 \cdot 378^2 - (0 \cdot 756 \times 0 \cdot 527)} = 1 \cdot 35$$

(*b*) Increase by eddy currents at 98 cycles per sec. (from Field's curves) = 1·36

(*c*) Increase by resistance (from Fig. 3) = 1·14

Total rotor copper loss .. .. = 2 030 × 1·35 × 1·36 × 1·14 = 4 250 watts.
Allowance for iron loss in teeth .. = 260 watts.
Total rotor loss on short-circuit .. = 4 510 watts.

The probable full-load temperature-rise of the rotor may now be roughly estimated as (2 030/4 510) × 35 deg. C. = say 16 deg. C.

From Fig. 3 the increase in resistance from cold = 1·06.

Hence full-load rotor loss = 2 030 × 1·06 = 2 150.

And the probable full-load temperature-rise of the rotor (by Equation 5) is

$$\frac{2\,150}{4\,510} \times 35 \text{ deg. C.} = 16 \cdot 5 \text{ deg. C. (approx.)}$$

Probable full-load temperature-rise of stator by Equation (2), where V is assumed to be unity, is

$$36\left[\frac{2\,710 + 2\,720}{(4\,510 - 2\,150) + 2\,720}\right] = 38 \cdot 5 \text{ deg. C.}$$

The results of similar observations which were made on other machines are given in the table on page 1016.

VARIATIONS OF THE METHOD OF CONDUCTING THE TEST.

There are two principal deviations from the manner of carrying out the test on the lines previously described, and these are applicable to special cases, the main principles of reversed rotation and short-circuited secondary being adhered to in each case.

(1) A motor fitted with slip-rings capable of carrying the full-load rotor current continuously may be tested with its stator windings short-circuited and with a suitable supply voltage applied to the rotor. Normally the supply would be connected to the stator when the motor is in service, but if the test is arranged in this special way the stator windings carry the double-frequency current and the rotor current is at normal line frequency. This is particularly valuable for minimizing the losses due to eddy currents if the rotor bars are of heavy section and the stator windings of comparatively small section copper. The rotor current should be adjusted to a value corresponding to full-load current in the stator, where the full-load copper loss is to be produced. (It is presumed that the copper is small enough to allow the eddy-current loss at twice the normal frequency to be neglected.) In the rotor the current exceeds the value it would have at full load when the motor runs with the supply on the stator, and the extra rotor loss from this source and that loss contingent on the rotor frequency may be estimated on the lines already laid down. Hence the temperature-rise under these conditions on both stator and rotor windings affords a good indication of what may be expected on load if interpreted in accordance with the previous argument.

(2) It is sometimes found inadvisable to subject the rotor or the stator to currents which have a frequency double that of the line, owing to the prohibitive eddy-current losses which would result. The test on such a machine may be carried out by applying a supply voltage of half the normal frequency to the primary, still maintaining the normal speed of the rotor in the reverse direction. If f_1 = the normal frequency, the applied frequency is $\frac{1}{2}f_1$, and, since the rotor is running at nearly double the synchronous speed relative to $\frac{1}{2}f_1$ but in a reverse direction, the frequency of the secondary current is

$$\frac{f_1}{2} + \frac{2f_1}{2} = \frac{3}{2}f_1$$

which will help to keep down the eddy-current losses and, incidentally, the iron losses due to stray flux.

The figures and tests relating to actual motors are used by courtesy of The Brush Electrical Engineering Co., Ltd.

THE REGULATION OF THE EARTH POTENTIALS OF ALTERNATING-CURRENT SYSTEMS.*

By T. R. WARREN, B.Sc.(Eng.), Student.

(*Paper first received 5th January, and in final form 20th March*, 1925.)

SUMMARY.

The determination of the change in the value of the earth potential of any part of an alternating-current system, when that part is earthed through an impedance of known value, is one of the primary aims of this paper. The author has already investigated the problem for systems in which the earth capacity currents can be safely neglected,† but, since this condition does not always hold even approximately in practice, it is hoped that the complete solution of the problem will prove more useful.

The first part of the paper is devoted to the derivation of a simple equivalent network which represents the various leakage paths of the system, the method of solution being based on Kirchhoff's Law. The completeness of the theory in regard to its application under normal conditions of working is then demonstrated, and the effects due both to the presence of harmonics in the E.M.F. waves and to the voltage-drop along the mains are fully considered.

Following this there is a short description of methods to determine the values of F and K without interrupting the supply to the consumers. Formulæ are given which enable the separate values of f_1, f_2 and f_3 to be obtained in the case of three-wire three-phase systems.

The last section contains a discussion of the Petersen coil method of earthing, special reference being made to transient current phenomena. The dangers attending the use of the coil are explained, and it is pointed out that this method of earthing would be expected to fulfil the same duties on any type of alternating-current system, irrespective of the form of its voltage diagram.

INTRODUCTION.

It is now more than 20 years since experimental methods of determining the insulation resistance of direct-current systems under normal working conditions were first introduced, and in connection with these it will be sufficient to mention the names of Dr. A. Russell and Mr. F. C. Raphael. Dr. Russell also showed how the decrease in the earth potential of any main when connected to earth through a resistance of known value can be predetermined, provided the value of the insulation resistance of the system is known. This work has since proved to be of the greatest value to engineers both in the maintenance of supply mains and in the calculation of earthing resistances.

The need for dealing with alternating-current systems along the same lines soon arose with the advent of the more economical type of transmission, but, owing to the presence of the capacity effect between the mains and earth, it did not appear that the complete solution of the problem would, if obtainable, prove simple enough for ordinary practical purposes. It will be seen, however, that there is a distinct parallel between the alternating-current and the direct-current cases, the latter being merely a particular case of the former. This statement will become perfectly clear if we first examine the formula which gives us the insulation resistance F in terms of V, the earth potential of one of the mains, and V', the new potential when this main has been connected to earth through a known resistance x; for we have

$$F = \frac{V - V'}{V'} x$$

and the value of V' in this expression is clearly consistent with the value of the E.M.F. across a resistance x which is itself in series with a resistance F, the whole circuit being supplied with an electromotive force V. The existence of the equivalent network in the d.c. case at once leads us to suppose that a similar network possibly exists in the case of a.c. systems. It will be made abundantly clear in what follows later that this is indeed the case.

In arriving at the above formula it has been usual to assume that (1) all the leakage paths are located in the mains, and (2) each main is at the same potential throughout its length. Now, strictly speaking, neither of these assumptions is always realized in practice and, moreover, neither of them is actually necessary in proving the theory. Thus, instead of considering finite portions of the systems which are supposed to be at the same potential, we shall consider a given point and investigate the leakage current from it. The voltage diagram provides us with a convenient method of illustrating the problem, since actual points on the system can be represented by means of corresponding points on the diagram.

DERIVATION OF THE EQUIVALENT NETWORK.

In order to avoid the possibility of confusion arising over the use of certain terms, it is necessary to define what is meant by "insulation resistance" and "earth leakage capacity." By these we mean the resistance and capacity respectively between the various parts of the system and earth. These terms, therefore, do not take into account the leakage paths between the various parts of the system itself, because any currents flowing through these are merely in the nature of an ordinary load, and, since they do not flow to earth,

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† T. R. WARREN: "The Measurement of Insulation Resistance," *Electrical Review*, 1923, vol. 93, p. 151; also E. MARX: "Locating Earth Potential in Three-phase Installations and Measuring Insulation Resistance of High-tension Installations during Service," *Elektrotechnische Zeitschrift*, 1922, vol. 43, p. 1409.

they do not in any way affect the values of the earth potentials.

We shall first consider the case of a polyphase system in which the potential waves are sine-shaped, so that all the alternating quantities considered may be represented by means of systems of co-planar vectors. The more general case in which harmonics are present will be dealt with afterwards by means of the method of superposition. In Fig. 1 let PQ be any axis fixed with reference to the voltage diagram of the system, and let O be the point of zero potential. Since O is free to move in a plane, its position is expressed as a function of two independent variables, and two equations will therefore be necessary to locate it; these equations are deduced from Kirchhoff's Law.

If A is any point of the system whose earth potential is represented by the vector OA making an angle θ

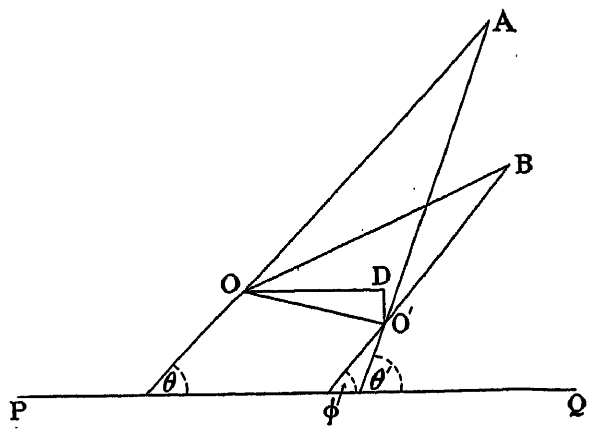


FIG. 1.—Vector diagram showing effect of earthing at B.

with the fixed axis, the leakage current C_A at A will be given by

$$C_A = \mathrm{OA}\sqrt{\left\{\left(\frac{1}{f_A}\right)^2 + (\omega k_A)^2\right\}}$$

where f_A = the insulation resistance at A,
k_A = the earth leakage capacity at A, and
$\omega = 2\pi \times$ frequency.

Also by Kirchhoff's Law we have

$$\Sigma C = 0$$

the symbol Σ denoting a vector sum. Therefore by resolving all the components of the leakage currents in directions parallel and perpendicular to the fixed axis we obtain, as the two equations determining the position of O,

$$\Sigma\frac{\mathrm{AO}}{f_A}\cos\theta + \Sigma\mathrm{AO}\omega k_A\cos\left(\theta+\frac{\pi}{2}\right) = 0$$

and $$\Sigma\frac{\mathrm{AO}}{f_A}\sin\theta + \Sigma\mathrm{AO}\omega k_A\sin\left(\theta+\frac{\pi}{2}\right) = 0$$

These may be written

$$\Sigma\frac{\mathrm{AO}}{f_A}\cos\theta - \Sigma\mathrm{AO}\omega k_A\sin\theta = 0 \quad . \quad . \quad . \quad (1)$$

$$\Sigma\frac{\mathrm{AO}}{f_A}\sin\theta + \Sigma\mathrm{AO}\omega k_A\cos\theta = 0 \quad . \quad . \quad . \quad (2)$$

If we now earth any point B (say) through a resistance x and a reactance r, then O will take up some new position O′, and (1) and (2) become

$$\Sigma\frac{\mathrm{AO}'}{f_A}\cos\theta' - \Sigma\mathrm{AO}'\omega k_A\sin\theta' + \frac{\mathrm{BO}'}{x}\cos\phi + \frac{\mathrm{BO}'}{r}\sin\phi = 0 \quad . \quad (3)$$

$$\Sigma\frac{\mathrm{AO}'}{f_A}\sin\theta' + \Sigma\mathrm{AO}'\omega k_A\cos\theta' + \frac{\mathrm{BO}'}{x}\sin\phi - \frac{\mathrm{BO}'}{r}\cos\phi = 0 \quad . \quad (4)$$

where θ' is the new value of θ, and ϕ is the angle made by BO′ with the fixed axis.

In the two preceding equations r is assumed to be inductive, but the alternative case in which it takes a leading current is easily taken into account by changing the signs of the terms in question.

By subtracting (1) from (3) and (2) from (4) we have

$$\Sigma\frac{\mathrm{OD}}{f_A} - \Sigma\mathrm{O'D}\omega k_A + \frac{\mathrm{BO}'}{x}\cos\phi + \frac{\mathrm{BO}'}{r}\sin\phi = 0$$

$$\Sigma\frac{\mathrm{O'D}}{f_A} + \Sigma\mathrm{OD}\omega k_A + \frac{\mathrm{BO}'}{x}\sin\phi - \frac{\mathrm{BO}'}{r}\cos\phi = 0$$

where D is the point of intersection of the parallel to the axis through O and the perpendicular to the axis through O′ (Fig. 1).

Since OD and O′D are constants, these equations may be written

$$\frac{\mathrm{OD}}{F} - \mathrm{O'D}\omega K + \frac{\mathrm{BO}'}{x}\cos\phi + \frac{\mathrm{BO}'}{r}\sin\phi = 0 \quad . \quad (5)$$

$$\frac{\mathrm{O'D}}{F} + \mathrm{OD}\omega K + \frac{\mathrm{BO}'}{x}\sin\phi - \frac{\mathrm{BO}'}{r}\cos\phi = 0 \quad . \quad (6)$$

Let us next replace all the leakage paths of the system by a resistance F and a condenser of capacity K at O, and suppose that the point of zero potential is now at some new point O″, while D is at some new point D′. Then by resolving the currents as before we get

$$\frac{\mathrm{OD}'}{F} - \mathrm{O''D'}\omega K + \frac{\mathrm{BO}''}{x}\cos\phi' + \frac{\mathrm{BO}''}{r}\sin\phi' = 0$$

$$\frac{\mathrm{O''D'}}{F} + \mathrm{OD'}\omega K + \frac{\mathrm{BO}''}{x}\sin\phi' - \frac{\mathrm{BO}''}{r}\cos\phi' = 0$$

where ϕ' is the new value of ϕ.

These equations are clearly similar in form to Equations (5) and (6) and, as in the previous case, they are each functions of the two variables which determine the position of O″. This being so, it is clear that the positions of O′ and O″ are each determined as the same function of the quantities F, K, x and r, and consequently these two points must coincide. This leads us at once to the important conclusion that the potential of any part of the system is regulated as though all the leakage paths are concentrated at a point of zero potential. The meaning of this is conveniently illustrated by means of the equivalent network shown

in Fig. 2, in which F and K in parallel are in series with x and r in parallel; the E.M.F. applied to the network is the original potential of the part of the system earthed, whilst the E.M.F. across x and r is the same as in the actual case.

In obtaining this result it has been assumed that the shape of the voltage diagram has not altered during the test, apart, of course, from the shifting of the point of zero potential. This assumption is perfectly admissible, provided that the load remains approximately constant, and also that the current through the artificial leak is not large, as otherwise there will be distortion due to voltage-drop. It is easy to see that the latter consideration interferes with the investigation of cases where heavy fault currents occur, since a correction now has to be applied which depends upon the constants of the system.

Before proceeding to investigate the applications of the theorem, it is important to determine the effects due to the presence of harmonics in the E.M.F. waves and to see whether the theory has to be modified in any way. The answer to this is readily seen if we consider each harmonic to exist separately; the equivalent network obtained in each case is the same, since the values of F, K, x and r are independent of the frequency. Thus, by superposing on one network the various harmonic components of electromotive force, the resulting current will be identical with the actual current flowing through the artificial leak.

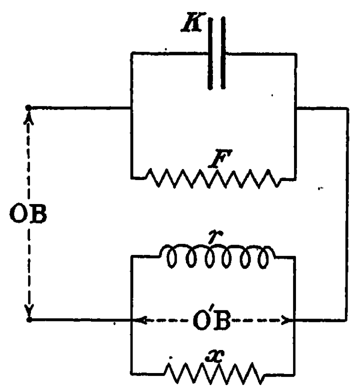


FIG. 2.—Diagram illustrating the equivalent network.

Practical Applications.

One of the most important questions with which station engineers have to deal is the interruption of supply due to faults. In the case of high-tension systems, experience shows that faults frequently occur on mains which are apparently sound, and thus we have no means of predicting their occurrence. In low-tension systems, however, faults are usually preceded by a gradual deterioration of the insulation of the faulty section, thus giving warning of the approach of a breakdown. The importance of being able to keep a continuous record of F can, therefore, hardly be over-estimated, since a sudden decrease in its value may always be taken to herald the approach of trouble, whatever the type of system may be.

It may be mentioned that cables embodying "test sheaths" are being received with increasing favour by the electrical engineering industry, since these enable the insulation resistance of that part of the cable exterior to the sheath to be found separately for each feeder. In this way the faulty sections are immediately located, and, where possible, repairs are executed.

The importance of knowing the value of K is, in general, less than that of knowing F, but exceptions occur in cases of systems earthed through inductances. In particular we might take the case of the Petersen coil which is more fully considered in the last section. With this type of earthing, the effect of the capacity is neutralized by the inductance of the coil which is tuned to resonance with it at the fundamental frequency. Knowing K, therefore, the value of the inductance required is also known, and the coil can then be designed accordingly.

Another important class of problem which calls for solution is the following. Suppose we wish to reduce the potential of any part of a system to a given value. What earthing resistance will have to be connected to this part in order to effect this? The answer to a problem of this type is easily calculated from the equivalent network, provided we have previously found F and K, methods of doing which will now be suggested.

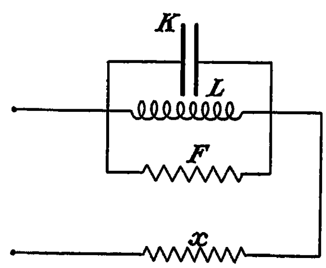


FIG. 3.—Diagram showing how the capacity effect in a system is neutralized by means of an inductance.

Determination of F and K.

The method of procedure which appears to be the most convenient from a practical point of view is as follows. Connect a variable inductance between any convenient part of the system which is at a low potential and earth, at the same time noting the voltage across it by means of an electrostatic voltmeter. When the reading on the meter reaches a maximum value for a given value L of the inductance, then K may be found from the formula

$$K = \frac{1}{\omega^2 L} \qquad (7)$$

This relationship is only strictly true when no harmonics are present, but, in cases where a serious error may be introduced by making such an assumption, resonance with one of the harmonics can easily be obtained by means of an oscillograph, and the value of K can then be found.

If the inductance is retained in position, the system now virtually possesses fault resistance only, as is easily seen by the equivalent network (Fig. 3) which

represents this new condition. It follows at once that F may be found by connecting a known resistance x between any part of the system and earth, and then, by noting the potential V before the connection is made and its new value V' afterwards, we get

$$F = \frac{V - V'}{V'}x \quad . \quad . \quad . \quad . \quad . \quad (8)$$

An easy way of obtaining the total fault impedance is to observe the potential V'' (say) of any part of the system and the current I which flows through an ammeter connecting this part direct to earth. We then find

$$\frac{I}{V''} = \sqrt{\left\{\left(\frac{1}{F}\right)^2 + (\omega K)^2\right\}}. \quad . \quad . \quad (9)$$

By the use of this formula we need not know the value of L in (7), since K may be found from (8) and (9) to be given by

$$\omega K = \sqrt{\left[\left(\frac{I}{V''}\right)^2 - \left\{\frac{V'}{x(V - V')}\right\}^2\right]} \quad . \quad (10)$$

This formula, however, will not give reliable results when ωK is small compared with $1/F$, since small percentage errors in the meter readings may introduce in this particular case a large error in the value of K. Generally speaking, therefore, it will be better to use a calibrated inductance and so be able to read the value of L.

We may take as an example a system having a frequency of 50 cycles per second. If L is $0 \cdot 5$ henry, then

$$K = \frac{10^6}{(2\pi)^2 \times (50)^2 \times 0 \cdot 5}\mu\text{F} = 20 \cdot 5 \ \mu\text{F (approx.)}.$$

If we now earth through a resistance of 50 ohms, thereby reducing the potential from 60 volts (say) to 11 volts, we find from (8) that

$$F = 50\left(\frac{60}{11} - 1\right) \text{ ohms} = 222 \cdot 7 \text{ ohms (approx.)}.$$

The reciprocal of the total fault impedance is, therefore,

$$\sqrt{\left\{\frac{1}{F^2} + (\omega K)^2\right\}}$$
$$= \sqrt{\left\{\left(\frac{1}{222 \cdot 7}\right)^2 + (100\pi)^2 \times (20 \cdot 5)^2 \times 10^{-12}\right\}}$$
$$= 0 \cdot 0078 \text{ (approx.)}.$$

If, therefore, we wish to apply formula (10), we should find that the current flowing through a dead earth at a point originally at potential 100 volts would be $100 \times 0 \cdot 0078$ ampere, or $0 \cdot 78$ ampere. By observing this ammeter reading we may deduce the total impedance when L is not known, and by the application of formula (10) we find

$$\omega K = \sqrt{\left[\left(\frac{0 \cdot 78}{100}\right)^2 - \left\{\frac{11}{50(60 - 11)}\right\}^2\right]}$$
$$= 6\,430 \times 10^{-6}.$$

from which $K = 20 \cdot 5 \ \mu\text{F}$ as before.

It is an interesting fact that the power consumed in the resistance x in formula (8) reaches its maximum value when $x = F$. It is unfortunate, however, that in most of the cases met with in practice this power is too small to be measured conveniently by a wattmeter, for otherwise we should be furnished with a convenient method of measuring F directly from a calibrated resistance.

In order to keep a watch upon the state of the insulation resistance of three-phase systems, electrostatic voltmeters are sometimes connected between the mains and earth, a low reading on one of the meters being taken to indicate that a fault is developing in the main to which this particular meter is connected. The objection to this method is that it does not show whether all the mains are deteriorating at the same time, and from this point of view it is perhaps better to use mains constructed with test-sheaths. The following method of determining the insulation resistance of each of the three mains separately, assuming that all the leakage paths are located in the mains, may be applied to low-tension systems.

The first step is to earth through an inductance so as to neutralize the capacity effect as previously explained. Let V_1, V_2 and V_3 be the resulting potentials of the three mains, while V denotes the line voltage. Now earth the main having the potential V_3—choosing it so that it is greater than V_1—through such a resistance x (say) that the new potentials V_1' and V_3' are equal. Then the author has shown * that the required resistances f_1, f_2 and f_3 are given by the following formulæ :—

$$f_1 = \frac{\sqrt{3}VFx}{V_2'(F + x)}$$
$$f_2 = \frac{\sqrt{3}VFx}{(\sqrt{3}V - 2V_2')(F + x)}$$
$$f_3 = \frac{\sqrt{3}VFx}{V_2'(F + x) - \sqrt{3}VF}$$

where V_2' is the new value of V_2 and

$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} + \frac{1}{f_3}$$

But we already know that

$$F = x\left(\frac{V_3}{V_3'} - 1\right)$$

and by substituting this value of F in the above formulæ we have finally

$$f_1 = \frac{\sqrt{3}V(V_3 - V_3')x}{V_2'V_3}$$
$$f_2 = \frac{\sqrt{3}V(V_3 - V_3')x}{(\sqrt{3}V - 2V_2')V_3}$$
$$f_3 = \frac{\sqrt{3}V(V_3 - V_3')x}{V_2'V_3 - \sqrt{3}V(V_3 - V_3')}$$

* *Loc. cit.*

THE PETERSEN COIL.

The method of earthing systems by means of inductances is one which has received more favour abroad than in this country, so a few remarks on this subject given in the light of the present theory will no doubt be of interest to a great many of those who study Continental practice.

The particular value of earthing inductance which produces resonance with the capacities of the cables constitutes the well-known Petersen coil. It is clear from what has been said before that under normal conditions the coil will have the effect of raising the potential of the main to which it is connected by an amount which is limited by the value of F, and that unless this value is determined under the most favourable conditions, i.e. in dry weather and during light load, we are relying for safety upon an unknown factor —a policy which, though not to be commended, is often pursued.

Another apparent source of danger lies in the possible increase of the "residual" voltage of three-phase systems due to possible unbalancing of the insulation resistance of the mains such as might occur when a consumer switches on a piece of apparatus which is slightly faulty. This appears to account for the failure of some systems to give good results with this type of earthing. With overhead transmission lines it is usual to balance the capacities of the mains as far as possible by transposing the wires at regular intervals; in this way the risk of breakdown is reduced to a minimum.

Under fault conditions the fundamental-frequency current flowing through the fault is merely that due to the faulty insulation of the rest of the system, and, in the case of a dead earth, is obtained by dividing the original potential of the faulty part by F; in general, this current is negligibly small. It is found that this diminution of fault current is accompanied by an almost complete suppression of the troublesome high-frequency oscillations which are usually produced in high-tension systems under fault conditions. Several suggestions have already been advanced as to why the "Petersen coil" method of earthing is so much superior in this respect to the resistance method.

One explanation at least may be obtained from the equivalent network, because a little consideration will be enough to convince us that there is no tendency for transient currents to flow through the fault at all, since there is no inductance in series with K. On the other hand, if the coil were replaced by a resistance so that the fault current is considerably increased, the effect would be to alter appreciably the potential of every part of the system owing to the voltage-drop along the mains and in the generator and transformer windings. It will be recalled that the theory given above does not take this case into account, but the effect of thus distorting the voltage diagram will be easily understood. For example, if the effect is to change the potential of some point A, while the potential of another point B is changed to the original potential of A, then the fault impedance at A appears to be in series with the impedance of the section AB. From this it would appear that the capacity K is, in this case, virtually in series with an inductance which depends upon the line constants, and in this way we can account for the presence of the familiar transient currents.

Since, as we have seen, the theory which has been investigated does not depend in any way upon the type of distribution employed, it follows that the Petersen coil can be used with equal success in connection with any type of a.c. system, irrespective of phase. This property of the coil is perhaps of little value at present in these days of three-phase transmission, but multiphase transmission at 110 000 volts has already been suggested as a possibility for the future, and the problem of eliminating interference with telephone circuits will then perhaps call for a revision of the methods of earthing at present employed.

DISCUSSION ON

"THE DESIGN OF ELECTRICAL PLANT, CONTROL GEAR AND CONNECTIONS FOR PROTECTION AGAINST SHOCK, FIRE AND FAULTS."*

North-Eastern Centre, at Newcastle, 23 February, 1925.

Mr. R. W. Gregory: The high standard of service required from the electric supply undertakings in this country, and the high standard of safety required to meet the various Government Regulations in connection with the supply and use of electricity, are perhaps the primary reasons for metal-clad switchgear. The electric supply undertakings in England have never had the pioneering freedom which is the outstanding feature of electrical development in the United States. For this reason, instead of developing a general system of high-tension overhead distribution and workmen not afraid of high voltage, we have in this country developed the arts of making underground cables and metal-clad switchgear. Development on these lines has probably cost us more per unit sold, but at least we have had the satisfaction of approaching perfection in the practice of these arts. Within the limits of the distribution pressures common in Great Britain, iron-clad switchgear has proved to be sound engineering. The compact, fully interlocked, factory-assembled switch-panel is an excellent engineering job, giving what might be termed the "Rolls Royce" service generally expected by the British consumer. The world-wide researches on oil circuit-breakers do not yet appear to have provided data for direct design, such as is possible with the steam engine or gas engine, but they have, together with increased experience in service, added greatly to the general knowledge of circuit-breaker design, and buyers in this country have now a wide market in which to obtain good circuit breakers capable of giving efficient service. The commercial and economical use of the science of breaking capacity is an interesting problem. In practice, on a soundly designed system using underground cables and metal-clad switchgear, the maximum fault is a very rare occurrence, and in many places it is often technically and commercially sound to use switchgear rated at less than the maximum fault kVA. Where this course is followed, it is necessary to make sure that the operator is not exposed to danger when closing a switch on a fault. For this reason, remote operation is desirable. With regard to power station switchgear, it is interesting to compare the development in this country with that in America. The switchgear in the Carville "B" power station of the Newcastle Electric Supply Co. was erected about the same time as the switchgear for the Calumet station in Chicago. The problems to be solved in both stations were practically the same, but the method of solving was entirely different. It was realized by both parties that it was essential to do the utmost to prevent a fault between phases. The Carville method of meeting this point was to build a strong compact gear in which earthed metal everywhere surrounded each phase. The Calumet method was to provide an entirely separate room for all the apparatus and conductors belonging to each phase. The differences in dimensions and appearance between the two types of gear are considerable. It shows how marked is the difference between the two countries in switchgear engineering practice. One of the most important problems in high-tension switching is the provision of cheap apparatus suitable for using on large power systems, and at the same time meeting the stringent requirements of operating staffs and Government Regulations. Cheapness is best obtained by reducing the amount of apparatus used and by making that which remains the best possible. The switch-fuse described by the author, and the single-switch substation, are attempts to reduce the cost of switchgear necessary for a high-tension supply and at the same time to give the service and safety necessary for British conditions. The author has not mentioned in his paper the question of switchgear control. Centralized control of system switching is now considered to be essential practice on large power networks, and the control engineer (or load despatcher) should know as quickly as possible whenever and wherever a switch has operated. There are now on the market several types of apparatus which, by the use of telephone cables, are able to perform this function. The next step, which I am sure will be generally adopted before many years elapse, is the actual physical control and operation of important switches on the system from the central control room. With automatic indication and supervisory control, the maintenance of service will be made easier and more secure and shut-downs over large areas, if not entirely prevented, will at least be of the shortest possible duration.

Mr. F. H. Williams: According to the author, the essentials of good switchgear practice are "simplicity" and "security," and no one who has to deal with large power schemes will fail to agree with this. Design of such switchgear is really a matter of faith and ideals. The author believed that he could design and manufacture, as a commercial article, switchgear which could stand up to any conditions likely to arise in practice, and events have justified this confidence. Other manufacturers, particularly on the Continent and in America, apparently not having the same faith in their products, have thought it necessary to introduce various additional devices to reduce the short-circuit forces. These devices, in addition to requiring extra maintenance, sometimes introduce further complications and, in the very nature of things, must be an additional source of weakness. The charging resistance mounted on the cross arm referred to in the paper is one such device, and is standard practice for all high-tension switches with one of the

* Paper by Mr. H. W. Clothier (see page 425).

biggest switchgear makers on the Continent. This manufacturer also uses the multiple-break system referred to by the author, increasing the number of breaks with the kilovolts of the circuit. One would have thought it an obvious source of weakness to mount this resistance on the cross arm. It cannot be too strongly emphasized that the simpler the switchgear, other things being equal, the better it is. I do not think the author claims sufficient credit for the compactness of the ironclad gear, and it would have been instructive to have, as an appendix, the comparative total cost (including buildings) of a switch-house for metal-clad gear and open-type gear based on the same kVA rating. It is difficult, for instance, for anyone unacquainted with metal-clad gear to realize that the unit shown in Fig. 7 houses, in a total height of under 10 ft., gear which in cellular construction, with about the same floor-space, would have to be accommodated on three or four floors, with a total height of 30 to 40 ft. The saving in buildings is really most striking, quite apart from the advantages of cheaper maintenance and greater security. If one may venture to criticize the paper, I would suggest that its value for reference purposes would be increased if the footnotes were amplified. I should also like to ask the author for further particulars of the semi-fluid insulating compound referred to on page 429. I have not come across this and, offhand, it does not sound very inviting.

Mr. N. Thornton: The principle of metal-clad switchgear is undeniably sound and affords many advantages, the chief among which are: the extreme compactness of the gear, so requiring only a small building in which to house it, and that without any cubicle structure, screenwork or other special forms of guarding; the ease with which it lends itself to any desired scheme of interlocking; and the fact that cleaning and maintenance are reduced to a minimum. It has, however, one drawback, in that it increases the length of a shut-down when it is necessary to make additional connections to the busbars, a point which is of some importance when considered in relation to the supply to domestic networks. Unfortunately, too, it has generally been found that the initial cost of metal-clad switchgear was greater than that of open-type switchgear, but this has to a large extent been offset by the reduced cost of buildings. The increased adoption of metal-clad switchgear tends to indicate that the general opinion is beginning to appreciate that any such increased cost is warranted by the subsequent decreased cost of maintenance and repairs. The split-conductor system is referred to as being an exceptionally useful and economical form of protection, which is quite correct, but it must be borne in mind that this condition only obtains so long as the feeder is required as a direct connection between two points. Immediately it is desired to give intermediate supplies off that connector the situation is altered and this type of protection is no longer consistent with economy of switchgear. This is of particular importance where intermediate supplies may be required for domestic networks, in which case the capital cost is all-important. The cost of taking supply by means of a loop-in of the split-conductor feeder, and of providing two split-conductor feeder panels in addition to apparatus required to control the intermediate supply, would in many cases prove to be prohibitive.

Mr. J. Rosen: In Fig. 36 the author has shown an arrangement for bringing the alternator stator leads out at the side to a terminal box attached to the stator end shields. I do not entirely agree with this arrangement, as there is only a limited space available for such apparatus in the modern alternator end-shields. If a similar distance is allowed between each phase terminal, as is shown between the phase and earth terminals in the figure, the depth of the end shields will have to be increased. This, and other difficulties, would, I am afraid, render the proposal impracticable. The usual method is to bring the leads out under the end shields, as shown in Fig. 1; I prefer to use terminals bolted to the chimney of the stator casing, as it is advisable to have between the cables and the alternator windings a joint which can be readily broken should the alternator stator be lifted at any time. The author refers to the automatic arrangements for closing the ventilating system and shutting the steam stop-valves, in order to limit the possibility of a fire spreading inside an alternator. In this connection, the closed-circuit system of forced ventilation, in which a comparatively small quantity of air is circulating continuously, acts as a safeguard; if a fault occurs in the alternator the air system is filled with burnt gases and the fire is extinguished at once. Great care should be taken in the design of switchgear for turbo-alternator auxiliaries. Recently plants have been shut down due to the failure of auxiliary switchgear. This apparatus should be robust and have the number of accessories reduced to a minimum. The author refers to self-balanced protection. This is one of the most reliable devices which can be used to protect alternator stator windings. With reference to the sequence of control, I would emphasize the importance of the author's proposals, and take the opportunity of pointing out that the field switch without a discharge resistance should only be operated in an emergency and must not be operated when the main oil switch is tripped by hand for testing the switchgear. With the large amount of magnetic energy in the present-day large alternators when the field circuit is suddenly interrupted, high voltages are induced and heavy currents circulate which, if repeatedly applied, might in course of time damage the alternator.

Mr. B. H. Leeson (*communicated*): The author has very rightly described "Stability" as the "Criterion of Quality" of a protective system, and the expression of this as a numerical value is a very welcome step towards establishing a recognized method for the comparison of various protective systems. In furtherance of this desirable object I should welcome the author's opinion upon the following comments. I shall preface these by reference to Fig. D, which depicts in the form of a genealogical table, for clearness, the chief conditions and factors which have to be considered. This is self-explanatory and will help to illustrate the remarks that follow. The numerical value for stability ratio obtained by the author's method of dividing the maximum straight-through current by the fault setting will depend

solely upon the designer's or manufacturer's judgment regarding the minimum fault-current setting that can be safely adopted "without any risk of inadvertent tripping, after taking all the disturbing influences into consideration." Now it is just this degree of risk which has been taken, or, conversely, the margin of safety which has been allowed, that the operating engineer particularly wishes to know, and hence I think that any method of expressing stability should essentially give a definite measure of the manufacturer's conservatism, or otherwise, in the form of a safety factor. The fundamental conception of stability may be best expressed as the ratio of the minimum straight-through current in service which would be required to cause inadvertent operation of the protective gear, to the maximum straight-through current that can possibly flow in the system. This, however, is rather an impracticable method owing to the difficulty of obtaining tangible figures, particularly for the numerator, and further, this expression might lead an optimistic designer

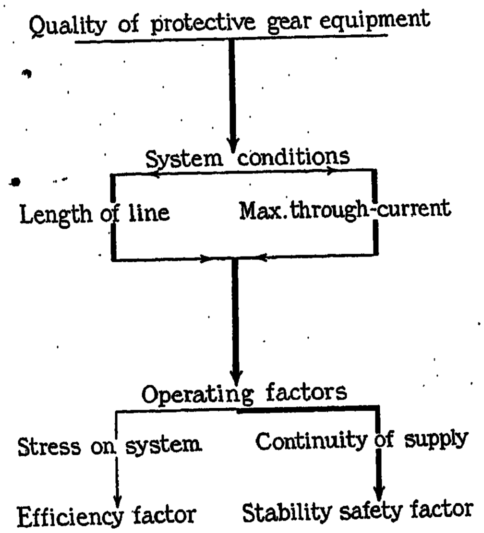


Fig. D.

to be tempted to make the numerator "infinity," thus falsely indicating infinite stability. I should therefore prefer to express stability in the form of a safety factor for a given straight-through current on the system as follows:—

$$\text{Stability safety factor} = \frac{\text{Service fault setting (actual)}}{\text{Minimum safe fault-current setting for stability, determined by tests (ideal)}}$$

In this expression the figure forming the denominator is obtained by an actual test carried out in such a manner as to reproduce as far as possible all the disturbing influences which will be met with in service for a given maximum value of straight-through current. The service fault setting is the actual value at which the relays will be set to operate in service, and the margin of safety above the test figure will allow for the hazards in service which cannot be faithfully reproduced artificially. By this means an operating engineer is given a definite idea of the margin of safety possessed by his protective system to ensure stability. The desirable value for this factor will depend upon the tactical importance of the protective gear on the system, but in any case I would suggest a minimum figure of 2, increasing this up to 4 in the more important cases. Following the author's lead in regard to stability, I think it would be desirable to introduce a term to show the relative efficiency of protective gears and I suggest the following expression:—

$$\text{Efficiency factor} = \frac{\text{Maximum straight-through current on the system (fault between phases)}}{\text{Service fault-current setting for given stability safety factor}}$$

This will give a numerical value to the efficiency of a protective gear after allowing a definite degree of stability, and the latter will guard against any false sense of security due to the rather natural appeal (at first sight) of low fault-current settings. The efficiency factor and the stability safety factor are naturally opposed to each other in principle. When judging the relative merits of these, primary consideration should be given to stability as the criterion of quality. It should be borne in mind that it is better to have lower efficiency and a reasonably heavy earth fault current to burn out and clear a fault immediately, than to have a higher efficiency with a light setting, risky stability, and then final resort to burning out the fault to determine its location. In addition to the stability of protective gear, "continuity of supply" depends primarily upon a high standard of insulation. It is a great pity that the rule for determining test-voltages in our B.E.S.A. Specification No. 116 should set a lower standard than that commonly used in the country from which it originated. The American manufacturers have virtually raised the standard by adopting, and applying the rule to, an arbitrary voltage rating for their switchgear which considerably exceeds the normal rated voltage of the system for which it is suitable. In view of this, the author's higher standard of pressure tests is to be strongly recommended. Since, however, insulation should not be judged entirely upon its ability to pass a high-pressure test successfully, it would seem desirable to follow along similar lines to the case of the protective gear and introduce a definite margin of safety to ensure that the test does not approach the ultimate breakdown point of the insulation too closely and thus perhaps tend to overstrain it. I suggest that this margin may also be expressed in the form of a safety factor as follows:—

$$\underset{\text{(for a given time)}}{\text{Insulation safety factor}} = \frac{\text{Minimum voltage at which ultimate breakdown occurs}}{\text{Specified test voltage}}$$

By specifying this factor of safety in conjunction with the test pressure, a purchaser would obtain a definite guarantee of insulation security with the knowledge and assurance that the insulation provided would not be liable to harmful over-stress during the test. The value of these safety factors is a matter for further research, but as a guide I would suggest that in cases

of puncture stress a figure of 2 should be taken as a minimum. I think it would be very helpful if the terms " efficiency factor," " stability safety factor " and " insulation safety factor " could receive the consideration of the B.E.S.A. with a view to introducing some form of standardization upon the lines indicated above.

Mr. L. E. Mold (*communicated*): The author has illustrated various methods which may be employed in transferring a circuit from one set of busbars to another either with or without interrupting the supply to that circuit. This operation has probably caused more interruptions to supply and accidents to operators than any normal routine duty in a power station. Admittedly, the accidents of which I have knowledge have occurred when operating open knife-type selector switches, and the methods recommended by the author eliminate this risk, but some of the designs illustrated introduce other serious dangers and risks. In Fig. 9 the operator is required to remove and insert plugs which engage with the busbars. The insulation on a loose piece of apparatus like a detached plug with an insulating handle is liable to damage, with consequent likelihood of a fatal shock to the operator. The removal of a plug whilst carrying current appears to be possible in certain conditions, and the resultant arc would be equally dangerous to the operator and to the switchgear. In Fig. 11 the change-over can be effected with reasonable safety, but the design entirely destroys the feature of safety usually associated with a duplicate busbar system. Connections from both busbars are brought into a common circuit-breaker tank, and it is reasonable to admit the possibility of failure due to an arc or its products in breaking a heavy fault current. Even under normal conditions with both busbars alive and unparalleled the voltage stresses may be doubled. Fig. 12 is safe in operation, since sound interlocks can be fitted, but it partly suffers from the disadvantage of the arrangement shown in Fig. 11, in that connections from both busbars are brought into one chamber although circuit-breaking does not take place in this chamber. Fig. 10 illustrates a very sound arrangement. If one circuit breaker only is employed the circuit must be broken to effect a change-over and if, in order to obviate this, two are employed the cost is greatly increased in the unnecessary duplication of parts. Fig. 8 is simple and effective, affords perfect safety to the operator, and ensures that the circuit is broken only in the circuit breaker; it is necessary, however, to open the circuit breaker to effect the change-over. My object in alluding to these features is an endeavour to ascertain whether the necessity really arises for the transference of a circuit from one busbar to the other without opening the circuit. The author advances sound arguments against this procedure (see pages 429 and 430). My own experience, and the result of many inquiries from station engineers, indicate that this function is more fanciful than necessary. The author has given four reasons justifying the necessity of a duplicate busbar, and these reasons consequently cover the necessity of changing circuits from one busbar to the other. A fifth may be added where certain feeders are required to operate at a different pressure, but the more convenient and economical method is to provide voltage regulators on the feeders. This leaves two conditions (1 and 2 on page 428). The first is of doubtful value and the second is nearly always met by the normal provision of busbar section switches which will enable all circuits from one section to be opened for a minute or so to effect the change-over. A reliable expression of opinion on this question would be of very great value.

[The author's reply to this discussion will be found on page 1031.]

East Midland Sub-Centre, at Loughborough, 10 March, 1925.

Mr. T. P. Wilmshurst: I quite agree with the author as to the advantages of metal-clad gear in eliminating danger and cleaning. One point is that there is no possibility of inspection where the apparatus is iron-clad. Is there not more difficulty in locating any fault which may develop? As our stations grow we have from time to time to consider the necessity of enlarging the sectional area of busbars, but with metal-clad gear it is impossible to do this. We have to deal with systems which have started from small beginnings, and with open-type cellular gear it is possible to make additions from time to time if necessity arises. An important point is that with cellular gear the conductors form their own diagram and a fault can be quickly located and easily put right. I should like to ask what is the correct protection for a unit transformer. Should there be any automatic protection between the stator terminals and the e.h.t. terminals of the transformer? With regard to overhead protection in rural districts where expensive switches cannot be afforded, has the author any experience with the tetra-chloride type of fuse and will he also say what type of fuse is used in the out-door substation shown in Fig. 27? Is there any danger to be anticipated due to the corona inside metal-clad gear tending to break down the insulation?

Mr. J. F. Driver: The author referred to the Rayworth pillar: this was an excellent type of switchgear, but the water switch gave trouble. One form of danger not mentioned in the paper, but which is serious, is a flash occurring close to an operator. This sometimes causes acute agony to the eyes. I am rather surprised that oil should be used in transformer junctions as a suitable insulating medium. In one case which came to my notice of an explosion due to an oil-filled junction box, what apparently happened was that the oil got hot due to a bad contact and boiled out, and possibly a small spark fired the gas and the transformer room blew up. I suggest that a material which would solidify would be better than oil. I do not understand the author's remarks with reference to lightning protection. I have not found lightning arresters very efficient on traction work. Has he seen definite signs that a lightning arrester has worked, i.e. has cleared a current-rush to

earth, particularly in a case where the discharge is supposed to dissipate its energy in the conductor itself?

Mr. T. Hall: Has the author had any experience with pole boxes? I have a system working at 11 000 volts and much trouble occurs with the type of pole box I am using, due to insulators breaking down. I have also had trouble on switchgear insulators, due to a static discharge, and I should be glad if the author would indicate the best way of getting rid of this.

Mr. H. V. Field: The introduction of reactance apparently does not limit the short-circuit power and protect the switches to the extent that would be expected, owing to the fact that the arc energy does not decrease in the same measure. Can the author suggest why that is the case? In regard to the curve given on page 430 for busbar current densities, what is the actual temperature-rise? The method employed for obtaining condenser protection against lightning and high-frequency transients by using half a mile of cable before joining up with the overhead line is very interesting. Has any trouble been experienced at the joint between the cable and the overhead line? With regard to Merz-Price balanced protective gear, Figs. 32 and 33 indicate great complexity and one wonders how such complex systems have come into use. Protective gear seems to be getting more complex than ever, instead of tending towards simplicity. In Fig. 20 the area for getting rid of gases and fumes seems to be a very good idea, but if the generators are laid out as shown this would not be a very good design of power house. One of the lantern slides exhibited showed a switchroom in which upward isolation was used, but it appears to me to be a very unsatisfactory layout. I should imagine that vertically downward isolation would have been much more satisfactory in that case.

[The author's reply to this discussion will be found on page 1031.]

NORTH MIDLAND CENTRE, AT LEEDS, 24 MARCH, 1925.

Mr. W. Howard Brown: I agree with the author that the time has come when we should cease to stress the advisability of purchasing duplicate switchgear, at any rate for ordinary industrial use; there is no more need to duplicate busbars than there is to duplicate main engines or turbines. It is now relatively easy to provide a.c. protection, but I should like the author to give us his views on the protection of d.c. plant, especially in regard to the sequence operation of circuit breakers and similar apparatus. I should also like his opinion as to the advisability of using resistance in series with fuses on the h.t. side of potential transformers. How far does he consider this practice can profitably be carried out in respect of comparatively small-power high-tension feeder circuits? It is interesting to note that the author throws some doubt on the advisability of adhering strictly to the B.E.S.A. specification for oil switches and suggests that alterations might very well be made. Many engineers, I think, will agree with him in this. I should be glad if he would give the result of his experience with lightning arresters as used on the North-East Coast undertaking.

Mr. J. W. J. Townley: I consider that under the conditions which obtain in this country armour-clad switchgear is the most suitable, and I venture the opinion, based on my experience with both open-type and armour-clad gear, that there will be very little open-type switchgear in use in 10 years' time. The serious defect of open-type or cellular switchgear is that once an arc is started a considerable number of panels can be put out of commission in a very few minutes, and with very little damage being done except to insulators and small connections which take a long time to replace. I know of one case in which an arc was started, due to the faulty operation of an oil switch, travelled up to and along the busbars and put seven panels out of commission by breaking busbar insulators; the capacity of the plant running was only 2 500 kVA. In another case an arc, started by the burning out of a current transformer on cellular open-type gear, destroyed five panels in 22 seconds. The capacity of the plant in this case was about 50 000 kVA. In each of the above cases the conductors were bare and the phases separated by slate or concrete barriers, which latter, however, had little effect in isolating the trouble. It is interesting to note that in modern cellular gear many designers are adopting the expedient of enclosing all conductors in insulated covering. Where the plant is of large capacity, on the occurrence of a fault the rupturing forces in metal-clad gear are likely to be of considerable magnitude, and extended experience in the behaviour of metal-clad gear under such conditions has yet to be gained. It must be admitted that the adaptability of such gear is not so great as that of open-type switchgear, but it is sometimes an advantage to know that extra-high-tension switchgear cannot be modified or added to excepting by the use of properly made details. The author advocates ruggedness in the design of protective gear, and this is one of the most essential points that station operators have to ensure. Protective gear has been installed in the past which has given much more trouble than the faults it is intended to guard against. Earthing resistances have been installed when plant capacities were small and have not been modified as the plant has been increased, and in many cases this results in the generating plant being almost entirely unprotected owing to the current passing the earthing resistance being insufficient to operate the relays. In view of the type of plant now being installed (turbo-generators) it is worth while considering whether the time has now come when the neutral point may be earthed solidly and without using expensive resistances. The question of interlocks on switchgear is not one for the decision of the switchgear manufacturers, who can usually supply any system of interlocking, but is one to be decided by the user. The arrangement shown by the author for changing over from busbar to busbar should meet all reasonable requirements in a power station, and I agree with him that such operations are relatively infrequent and should never be done

hurriedly. The author has given his opinion as to the breaking capacity required for any given size of plant, but has not suggested how we are to determine the breaking capacity of any particular oil switch excepting only on the basis of oil tank cubic content and strength. An amplification of the author's comments in this part of the paper would be appreciated.

Mr. R. M. Longman: Protective gear is blamed for much of the trouble that occurs, but in very many cases it is not given a chance, as it is connected up incorrectly. Has the author any experience of breakage or failure of a right-angle box in any of the positions shown on the lantern slides? With armour-clad gear the highest class of workmanship and material is absolutely necessary. Every manufacturer has, I think, fully realized that he cannot be too careful and particular in his inspection and examination. With regard to protection, it is sometimes asked what is the use of putting in relays and sensitive protective devices, when a fault might occur on a particular cable only once in five or ten years. The answer is, of course, that protection is not only to operate in the case of a fault but to prevent a sound section being cut out when the fault is beyond that particular section. I fully agree with the author on the question of the rating of switchgear, etc. It appears to me that the scheme shown in Fig. 28 has many advantages, one of which is the arrangement of the current transformers; nothing is left unprotected. In connection with the tee protection for the transformers, is any sort of overlapping arrangement provided so that should the fault on the transformer be rather more than the switch fuses could legitimately deal with, the section would come out?

Mr. S. D. Jones: It seems to me that the closed type of switchgear does make for greater efficiency. With regard to cleaning, much more of this is required with the open type than with the closed type. We are now connected up in parallel with the Yorkshire Electric Power Co.'s system. When I received tenders for the new switchgear connecting the two systems, I asked what the breaking capacity of the circuit breakers was, but could not obtain a satisfactory reply from the manufacturers.

Mr. W. D. Lovell: I am somewhat surprised that the author makes no reference to any type of closing device for use on direct-operated metal-clad gear, which can be temporarily attached to any switch mechanism, enabling the switch to be closed at a distance from the panel. In practice it often becomes necessary to switch-in doubtful apparatus, and the operator on these occasions runs a fair amount of risk unless some special form of closing device is available. One or two devices for this purpose have been developed and are being used successfully on some of the large power supply systems. The interlocking of duplicate busbars has caused a great deal of discussion for many years, and I fully agree with a previous speaker that it is more a matter for operating engineers than manufacturers to decide, as it depends largely on the design of each individual system. In view of the serious accidents that have occurred when changing-over circuits from one busbar to another while carrying load, I cannot help thinking that the opening of each circuit before the change-over is made, advocated by the author, is the correct method to adopt. The question of earthing has always been a very difficult problem on metal-clad gear, and although the arrangement shown in Fig. 24 appears to be a step in the right direction, there is still plenty of room for improvement. It would appear that before the arrangement suggested can be used on existing gear of some makes, it will be necessary to modify the shutters and oil-switch locking devices. On page 438 the author states: "If any mistake is made it will be no more serious than closing on a fault," and I should like to ask him whether this is quite correct. The earthing, unfortunately, is being done on the busbar side of the current transformers and outside the feeder protection, so that if by chance the feeder is alive, and assuming all three isolating plugs are short-circuited and connected to earth, the closing of the switch will produce a three-phase busbar fault. Should the feeder protection be of the balanced type it will be inoperative under these conditions and the fault will have to be cleared by the opening of the nearest sectionalizing switch, which on a ring system may be some considerable distance away. This may cause an interruption of supply over a large area. In connection with the "straight through" current rating, has the author carried out any experiments to determine the weakest link in the gear under these conditions? Referring to Fig. 3, will the author state what the disadvantages are in using three-core cable-dividing boxes in place of single-core sealing bells? In the former case, the three-core cable could be connected direct to the transformer, whereas the latter arrangement necessitates an additional dividing box. It is interesting to note that the author does not agree with the B.E.S.A. Specification No. 116 as regards breaking capacity, and I am sure that there are quite a number of operating engineers who are in agreement with him on this point. With reference to Fig. 37, showing the connections of self-balance protection for generators, I should be interested to know how the author proposes to protect the cables between the machine and switch. Presumably he would use Howard leakage protection.

Mr. D. M. Buist (*communicated*): I am entirely in agreement with the author in his criticism of the scanty attention paid to the terminals of alternators and motors. The criticism applies also to the methods of leading the connections from the windings to the outside of the carcase in the case of alternators, or to the terminal box in the case of motors. The standardization of terminal and cable-sealing boxes would be a boon to users. To my mind, compound filling is the only solution to all the difficulties encountered at this point, especially on motors, but the motor makers claim that it is difficult to seal the cable outlets against the compound, especially in warm situations. The remedy for this will be obvious to anyone with experience of metal-clad compound-filled switchgear. Transformer oil is indeed very penetrating. Much of the present trouble with junctions of porcelain and metal will disappear when the production of fused quartz on a commercial basis becomes practicable, and that day is not far distant. This material has a very high melting point,

the smallest expansion of any material, is more transparent than glass, is a better insulator than porcelain both mechanically and electrically, and consequently will have manifold uses in the electrical industry. Attention should also be paid to the cement employed with porcelain; I have known both oil and compound to leak past this cement. I agree with the author in regard to the duplication of components, but to be more definite I suggest that if a switch is purchased which is rated for twice the working pressure, twice the maximum full-load current of the circuit, and twice the breaking capacity required (according to the B.E.S.A. rating), then ample reliability will be obtained and there will be no need for spare switches. With regard. to duplicate busbars, the fact that all new stations possess them in some form or other is ample evidence of their necessity. The need for them in substations is dependent entirely upon their position in the network. The desire to be able to change over without making dead is a legacy of the open-type gear. In my opinion the only case which warrants it is that of an open-ended feeder. In all other cases I fail to see why the great advantage of simplicity should be sacrificed for this doubtful one. Until the results of the research at present being made into the design of oil switches are published, the relative importance of each of the factors affecting breaking capacity as enumerated by the author is purely hypothetical. For the same reason B.S.S. No. 116—1923 is not final, but is merely a guide in the matter of choosing an oil switch. Users must still, therefore, rely upon the experience of the makers in this matter and, in addition, for their own peace of mind, revert once more to the employment of factors of safety. I personally, as already stated, specify 100 per cent more than the B.E.S.A rating, and consequently it was with interest that I noted that the author recommends 70 per cent more. To deal with all the factors would take too much time, but there is one point to which I should like to draw attention. The only part of an oil switch subjected to wear and tear in normal routine operation is the brush contact, and heating at this point due to bad contact should be carefully watched by the operating staff. The only safeguard is a periodical examination of the contacts. When purchasing a switch, however, the purchaser should attach as much importance to the millivolt-drop test across the contacts as to the pressure test. Some time ago two accidents, due to the presence of chargers, led us to investigate their utility or otherwise, and oscillograph tests certainly proved their effectiveness during the switching-in of large motor armatures. In my opinion, first in the interests of simplicity, and secondly because they are not always in circuit when wanted, they should be abandoned, but unfortunately some makers of certain types of plant still consider them to be a necessary evil. The author states on page 436 that "delicate fault-settings of relays are sometimes attempted by the use of large current transformers," and I am not quite clear as to his meaning. Does he refer to overload or to Merz-Price protection? Certainly to employ a ratio higher than is really necessary will entail a finer setting of the relay for a given primary fault current, but that anyone should increase the ratio solely with this object is beyond my comprehension. I am glad that the author calls attention to this point, because the indiscriminate choice of current-transformer ratios has an important effect upon the protection. Like chargers, excess-pressure dischargers also may be regarded as necessary evils in some cases. To install such apparatus, however, without a means of indicating whether they function or not is, in my opinion, quite useless. Referring to the subject of safety to men working on the line, is it not possible for the operator accidentally to place the earth contact in Fig. 24 on the busbar plug instead of the feeder plug? Interlocking entails complications and also engenders in the operating staff a false feeling of security. No interlocking system is 100 per cent mistake-proof, and I often wonder if an elaborate sustem might not cause as many accidents, due to over-trust in it, as would arise in a simple system without any interlocks at all. I suppose the solution, as usual, lies in a compromise. There is a plethora of protective schemes on the market nowadays, and improvements in existing schemes generally mean additional relays. Whilst sympathizing with the makers in their difficulties, I am afraid that the inevitable result of it all will be that the bewildered user will, in many cases, regret the departure from the original combined overload and leakage system, which possessed the great advantages of simplicity, robustness and absence of pilots and was easily understood by the operating staff. It is illuminating to compare the schemes adopted in all new stations throughout the world; a few are the simplest possible, others have installed all the schemes and complications in existence, while others have struck the happy medium. Every undertaking has its own peculiar conditions to meet, and if a maker keeps this in mind and concentrates his endeavours towards simplicity and reliability in the direction indicated in the paper, I feel confident that the nearest approach to the ideal system will be reached very soon. I like the term "stability ratio" and the purpose for which it is put forward, but I am rather afraid that users will not be able to employ it with confidence until standards are established for the two factors constituting the ratio. The author makes a similar remark with regard to the rating of oil switches on page 434 and to my mind, since both subjects are so closely related, the same bases might be employed for both. The author quotes stability ratios varying from 25 to 200, and I should be glad to know what in his opinion are good values for generators and feeders respectively. With regard to the neutral resistance, the more one studies the subject of protection the more one is driven to the conclusion that a resistance is unnecessary. It is really a question of stability versus resistance. Both are pulling opposite ways upon the relay settings, stability demanding a high setting and resistance refusing and, in fact, enforcing a lower setting. Viewed from another point of view, the presence of a resistance has one advantage only in that it limits damage to the alternator on the occurrence of an earth fault. In my opinion this advantage is purely theoretical, because exactly how much more the damage would be with a solid neutral can only

be guessed at, especially when one considers the extremely small values of earthing resistances, which values will become smaller and smaller (therefore entailing more and more space occupied) with the rapid increase in the size of alternators. On the other hand the absence of a resistance would afford such definite advantages as: (1) Higher relay setting, and therefore greater stability; (2) complete protection of alternator windings against earth faults; (3) quicker development of earth faults; (4) elimination of cost of resistance; and (5) saving of space required for resistance. With regard to advantage (3), the devotees of the resistance might say, "Not only quicker but more disastrous development of earth faults," and my answer to this would be that, as regards feeders, a more disastrous effect would be welcomed because it would enable faults to be located with more certainty and speed. As regards alternators, however, we come back to the point to which I have already referred as the only—and at that, doubtful—advantage of a resistance. If we assume, however, that it is indeed a definite advantage, is not the correct way of tackling the problem to let the fault develop quickly to a high value and trip it out quickly with certainty, rather than to let it develop slowly and trip it out at a slightly lower value with uncertainty? Let engineers ask themselves which of these two circumstances will cause more damage. Once an earth fault develops, the fraction of time corresponding to the difference in the two relay settings is negligible, and it also should not be forgotten that the fault may develop in that portion of the winding left unprotected due to the presence of the resistance. I do not quite agree with the author when he says that the need for sensitive settings is due solely to the desire to cut down the size of the resistance. It might be so where space is very limited, but in my opinion it is more often in order to protect as much of the windings as possible and to lower the fault tripping current at the same time, simply because it is taken for granted that a resistance is absolutely necessary. I am very interested to hear that the author does not favour the employment of reverse relays for generator protection, but as only one single-phase relay is necessary when used in conjunction with Merz-Price gear, I consider that the extra insurance which it affords is worth the slight extra cost, particularly where alternators vary greatly in size. This type of relay redeemed itself in my views during a recent accident when under a unique set of circumstances one such relay assisted in preventing a total shut-down. Under the title of self-balance the author describes an arrangement for alternator terminals which might well be applied to any machine, no matter what system of protection is adopted. As regards his views upon the sequence of tripping of the machine oil switch, main field and exciter field, this is largely a matter of opinion upon which not only makers but users differ. I can certainly support his statement in his concluding paragraph that overload devices are great offenders in inadvertent operations.

[The author's reply to this discussion will be found on page 1031.]

Western Centre, at Bristol, 4 May, 1925.*

Mr. R. Hodge: One very interesting item which I do not think has been mentioned by previous speakers is the suggested type of switchgear for outdoor feeder work for use in agricultural and outlying districts. I refer to the high-tension switchgear. If this piece of apparatus, after being thoroughly tried out, is proved reliable, it should greatly simplify the supply of electricity to outlying districts, as no doubt its cost will be well below that of circuit breakers.

Mr. C. T. Allan: It would be an advantage if ironclad switchgear could be arranged for phase-changing tails to the cables. It is easier to repair a cable joint after breakdown by allowing the core joints to be made as they come in the road, especially in wet weather, than by forcing the correct phases together. When a new supply is commenced, small-ratio current transformers for metering are necessary on account of the low load, but, when the load increases, larger-ratio current transformers will be installed. This is, however, difficult to do on ironclad compound-filled switchgear. We have attempted to overcome this difficulty by housing the meter and its current transformers in a separate open-type cubicle. It may not be as safe as the other method but it has given us no particular trouble. The cost of e.h.t. switchgear seems to increase at a very much greater ratio than voltage, making the capital cost prohibitive and supplies for rural districts impossible. This type of load will have to be catered for, for many reasons, one being that the farmers over whose land the pole lines run naturally endeavour to insist on a supply being given to their farm.

Mr. T. R. Kernick: When dealing with ironclad switchgear for general distribution, one point I should like to mention is the difficulty encountered when it is necessary to change-over phases after a feeder breakdown and repairs have been carried out, particularly on e.h.t. work. Another difficulty with this class of gear is the trouble experienced in getting at the necessary contacts when mains-testing has to be carried out. This generally involves the removal of the complete switch truck. The author refers to the merits of underground cables compared with overhead lines, especially as regards maintenance costs. With mains laid underground in districts where ground subsidence is common, the maintenance costs can be, and are, very much higher than those of overhead lines in the same area.

Mr. H. R. Beasant: The paper deals only with alternating current, but direct current is still used; for instance we are still employing it for traction purposes. Can the author supply any information in regard to the safe breaking loads on d c. circuit breakers, or in regard to the time taken to get rid of an arc? We have often tried to get this information from switchgear makers, but the reply is usually that "this breaker will break at many times its carrying capacity." If such information is not available I think that steps should be taken to supply it.

* The paper was read at Bristol by Mr. L. E. Mold on behalf of the author.

Mr. T. E. Lewis : Can the author say how the figures for ascertaining breaking capacity are obtained ?

Mr. T. H. Haigh : I gather from the previous discussion that the breaking capacity of a switch depends more on the size of the tank than on anything else. I understand also that the speed of break at the moment of opening is an important factor. It is now common practice for switch makers so to design their tripping gear that if the switch is closed on a fault it trips immediately the contact is made, with the result that at the moment of opening there is no speed whatever. Does this seriously affect the breaking capacity ?

Mr. S. B. Haslam : The paper makes but little reference to the use of metal-clad gear under colliery conditions, yet I think there is no doubt that the development of metal-clad gear is largely due to these colliery conditions. In South Wales especially it is nearly always necessary to use flameproof or explosion-proof gear and, to take one improvement only, there is no doubt that the excessive strength of the tanks and the increased breaking capacity of this class of gear have been brought about because of the precautions which are necessary for underground working. Mr. Allan mentioned certain conditions which have to be taken into account very carefully, especially at the present time when finance is the predominating feature. These conditions are of course due to the development of electricity in underground working, and it is really a very serious matter and one which requires careful consideration. Personally, I consider there is a great deal of danger in an indiscriminate use of reactors, and it is necessary that all conditions should be taken into account before they are used. Another source of trouble which is frequently overlooked is the question of relative speed in operation of different types of switches in series. In a recent experience a small modern distribution switchboard was connected by a short length of cable to a circuit breaker on the main board of a large power station. The large switch was intended to deal with bad faults and to protect the smaller switches, but owing to the smaller modern switches operating more rapidly they were disastrously stressed. In such circumstances a definite time-delay device must be used which will ensure the larger switch operating first for a heavy current fault, but for a small current fault the smaller switch may clear the circuit at the expiration of the time-delay. It is hardly necessary to emphasize the fact that the very greatest care should be exercised in the selection of materials used in metal-clad gear. The other point to which I should like to refer is the connections to the machines. It does seem absurd that whilst carefully designed boxes are considered to be a necessity on a switchboard, the cables are frequently connected with the machine in a haphazard manner. The paper shows us that the author has given a considerable amount of thought to this important point, and I should like to suggest that far more attention could well be given.

Mr. H. W. Clothier (*in reply*) : I propose to deal with the various points raised under the headings of the Centres where they were discussed.

Newcastle.

The discussion at Newcastle is significant, coming as it does from the home of complete metal enclosure, where there is plenty of experience as to its design and working conditions. Apart from a general agreement with the several contributions there are a few specific points which call for a detailed reply. I feel sure there is much in Mr. Gregory's statement in regard to automatic indication and supervisory control. I am satisfied that the future will bring a greater demand for designs to relieve much of the very onerous operating which is performed to-day by hand. The greater uses of electricity and the concentration of enormous power will call more and more for automatic control. Otherwise the responsibility of making rapid decisions correctly, especially during emergencies, would be likely to become almost intolerable. These thoughts lead me to disagree with such comments as those made by Mr. Cresswell at the expense of interlocking features. Admittedly, every interlocking device must be perfected, and I believe that with care it can be. After all, automatic control and automatic supervisory control are in themselves advanced interlocking features in that they reduce the chance of human error by placing the sequence of operating functions into a regular order.

Mr. Williams suggests an appendix showing total switch-house costs, including building. I agree that this would be instructive as a commercial basis between different types of switchgear, but I suggest that it does not come within the scope of a paper the purpose of which is to consider safety to life and security to supply. Moreover, there is difficulty in making a straight cost comparison owing to the great divergence in practice, in the layout of connections, duplication of switches, in the margin allowed on insulation and clearances and in other ways, but a comparison of building constructions between draw-out metal-clad switchgear and a well-known example of cell type switchgear in America is shown in cross-section in Fig. E. The circuit breakers have the same rated breaking capacity, although in the metal-clad gear the tanks and top plates are larger and stronger, and therefore may be said to have a larger factor of safety.

The footnotes in the paper are intended to give credit very briefly to the originators of the designs which are recorded.

The semi-fluid compound referred to is a heavy mineral oil which is suitable for filling chambers when the contents are required to be accessible. It flows sluggishly at 16° C. and freely at 60° C., and its specific gravity is 0·88 to 0·92. As it is fluid at the permissible temperatures of switchgear, oil-tight joints are usually essential.

Mr. Thornton's testimony in regard to decreased costs of maintenance and repairs should be noted. The time of shut-down in making busbar extensions may be reduced by the initial erection of busbars in complete sections with section switches or in the use of duplicate busbars, but as a matter of a practice it is usually possible for a skilled erector to make a busbar joint in an hour or so. Other work on extension parts may be carried out in safety up to this juncture, as only

earthed metal is accessible, even when an adjacent existing panel is alive. A tee off a split-conductor line can always be taken satisfactorily through a single split-conductor switch. In this respect the choice of protection is equally favourable to split-conductor and Merz-Price voltage-balance protection. But I agree with Mr. Thornton that the split-conductor system accommodation laterally on alternator end-shields for the three terminals in line. In the future if end-shields are made deeper for other reasons it may be convenient to revert again to the design shown in Fig. 36 (I refer him to Mr. Buist's contribution to the discussion). At all events I am glad to have his views on the routine of breaking field circuits, and agree to the necessity for

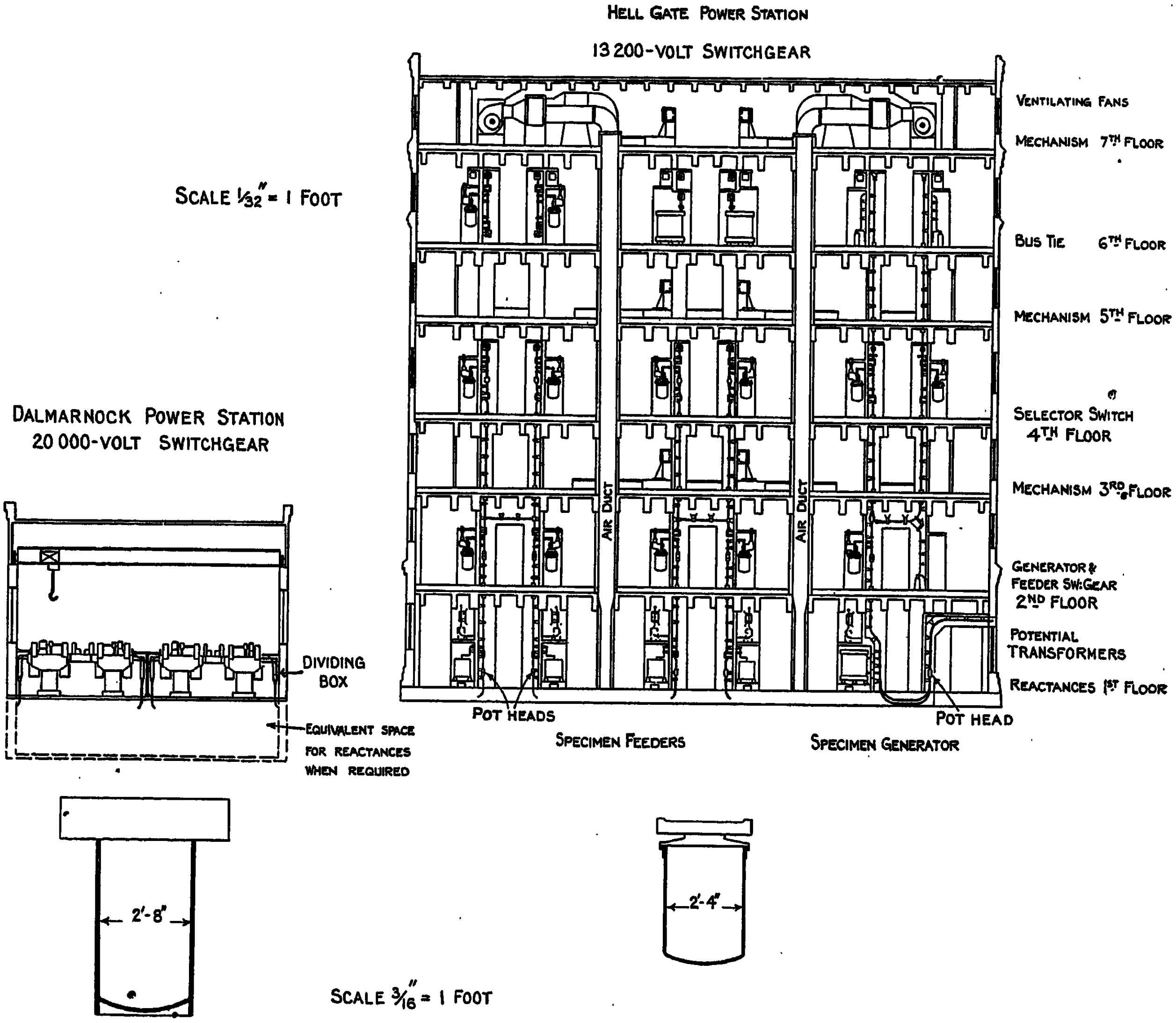


FIG. E.—Comparisons between Heil Gate and Dalmarnock power stations.

Upper figures (scale $\frac{1}{32}$ in. = 1 ft.)

Metal-clad gear, four panels, duplicate busbars, section through single phase. Single circuit breaker and two oil busbar selector switches per panel.

Open-type gear panels for two feeders or one generator section through three phases, duplicate busbars with two circuit breakers per feeder and three circuit breakers per generator.

For controlling a given number of generators and feeders the lengths of these two buildings would be approximately the same.

The lower figures (scale $\frac{3}{16}$ in. = 1 ft.) show the relative sections through the circuit breaker tank and top plate; both are rated at 1 500 000 kVA.

of feeder protection is inconvenient on feeders with tees when the tee is to be protected by a fuse for the sake of economy. It involves the use of a balanced reactance on each tee; these are not desirable additions to the switchgear apparatus.

I am disappointed that Mr. Rosen cannot find very sound construction of switchgear for power station auxiliaries and on self-balance protection. The importance of extinguishing the fire following a fault on the winding is felt so acutely that in some places a fire-extinguishing spray is contained within the machine. The speedy action of self-balance protection in isolating

the machine and simultaneously opening the field should go a long way towards the reduction of fire risks and the extent of damage occasioned by a fault. The world-wide use of one or other balanced systems for alternator protection is a striking acknowledgment of the pioneer work on protective systems done in the neighbourhood of Newcastle by the local power undertakings just on 20 years ago.

I would commend Mr. Leeson's alternative treatment of dealing with the need for a recognition of some form of stability factor to the British Engineering Standards Association, as I see no better means of encouraging a high standard of efficiency in this respect than by having an attempt made to establish the terms and measure of efficiency of protective systems. I agree that the minimum "stability safety factors" should be as follows :—

For voltage-balance feeder protection	2
For split conductor	4

(since the larger factor is easier to secure, retaining a light fault setting).

For generator protection current balance	4
For transformer protection current balance	2

The above figures to include all known hazards such as the magnetizing-current transient on transformers and resonance phenomena on feeders.

As a specification for protective gear one would include the following particulars :—

	Proposed standard terms
Required factor of safety between the actual service settings of relays and the test-room result on a circuit with equivalent characteristics	"Stability safety factor"
Maximum straight-through current possible between phases in the line to be protected with the ultimate amount of power plant behind, and making allowance for the impedance of all connections and intermediate equipment	"Straight-through" current
The minimum primary fault current between phases required to operate the relay in practical service	"Phase fault" current
Ratio : $\dfrac{\text{Phase "straight-through" current}}{\text{Phase "fault" current}}$	"Stability ratio" or "efficiency factor"
Minimum earth fault primary current to trip relays	"Earth fault" current
Maximum straight-through current to earth faults, having regard to the limitation of current imposed by the resistance of the return path via the earthing resistance	"Earth straight-through" current

Note.—When considering possible easement due to the "earth straight-through" current being less than the phase "straight-through" current, the adverse effects of simultaneous earth faults on different phases should not be overlooked.

I am in full agreement with Mr. Mold's reasoning in favour of the method of changing over from one busbar to another shown in Fig. 8. All the systems may be equally well interlocked to prevent mistakes and accidents, but with a varying degree of complication. The figures being only diagrammatic the interlocks are not shown, but it must always be the safer and simpler plan to open the circuit before effecting the change-over. Mr. Mold asks for a reliable expression of opinion on this subject. Other contributors have discussed it. I would refer him to the remarks by Mr. Townley and Mr. Lovell, also to those by Mr. Buist, who declares that "the desire to be able to change over without making dead is a legacy of the open-type gear."

Given a suitable layout of cables and plant, it should be possible for any one switch to be open without interruption of supply. Unfortunately some systems, e.g. single feeders starred out, are deficient in this respect. In such cases it is impossible to open any feeder switch without causing an interruption, and therefore occasions do arise in which it is out of the question to effect a change-over unless it can be done with the circuit alive. The need for such schemes as shown in Figs. 9, 10, 11 or 12 appears to be brought about entirely by these shortcomings in some system layouts. Owing to the greater operating dangers and interlocking complications of changing-over under load, it is best to continue with the simple plan shown in Fig. 8 in all ordinary situations.

Loughborough.

Mr. Wilmshurst agrees that metal-clad switchgear eliminates danger, but begrudges it the features of non-access which is the means by which that security is obtained. My best reply is to refer him to other speakers who are users of metal-clad gear, particularly those included in the Newcastle and Leeds discussions, but in addition I would suggest that it is a delusion to expect on large cell-type gears that the conductors form their own diagrams. It used to be so, but since they have grown and are now scattered upon different floors and compartments this advantage can

no longer be substantiated. If it applies at all it is to metal-clad gear nowadays, because the whole of the conductors are usually to be found upon one floor, and the path of the primary conductors could readily be painted upon the outside of the metal casing.

Mr. Wilmshurst makes a point of the possible need for increasing the sectional area of the busbar. When a station grows from small beginnings a time arrives when the switchgear originally installed, unless made large enough for the ultimate growth, must be taken out and, if it is in good condition, it may be moved to some less onerous situation. It is in such cases insufficient merely to add copper to the busbar sectional area, indeed that addition to large power station gear is a most unusual demand, for the reason that such gear is generally made up in sections of generators and outgoing feeders, each section carrying its own load from its generators. If a new generator is added it is usually because there are new feeders also, and these form the nucleus of a new section premeditated when the plant was first installed. The supposed impossibility of making additions to the sectional area of an existing busbar is not a material objection. One might almost as well call it an objection to cables and generators that their copper cannot be increased. It is not done. The demand in such cases is met by putting down new plant as extensions.

Mr. Wilmshurst inquires as to the protection of unit transformers for auxiliaries in large generating stations. These may be coupled on the high-tension side direct to the terminals of the alternator or to the switchgear, whichever is the shortest route for the cables. One switch panel controls the generator, its unit transformer and the cables. The automatic protection, whether Merz-Price current balance or self-balance, would have one common secondary system and relays.

I believe that the tetrachloride fuse serves a useful purpose economically when mounted well away from any operator. Its suffocating fumes must be a restriction otherwise. The fuse chamber in Fig. 27 contains nothing but ordinary switch oil. Any corona discharge inside metal-clad gear would be distinctly dangerous. Just as with open-type gear, it tends to weaken the insulation by forming nitrous acid. One feature of the metal-clad construction is that the compound- or oil-filling prevents internal air spaces and so avoids corona.

It will be of interest to present-day switchgear designers to hear of Mr. Driver's experiences with the water-break switches which form part of the early Rayworth pillars. These, with the exception of the actual switch, were pioneers of metal-enclosed construction. Mr. Driver's experiences with lightning arresters is confirmed by other speakers, and the subject is discussed below (see also the discussion before the Institution and my reply thereto).

Mr. Hall's experiences with pole-line insulators and switchgear on first consideration seem to point to an insufficient factor of safety in initial design, but this of course requires a closer investigation than I am able to make on the information supplied.

In reply to Mr. Field I will assume that the angle of lag of the short-circuit current is increased by additional reactance, and that an oil circuit breaker severs the arc, at the first zero value in the current wave, on short-circuit at unity power factor with comparative ease. With lag in current there is a tendency for the voltage to maintain the arc, and at a critical phase angle the arcs might be reinstated in passing through the zero value of the current wave, and hence the arc is prolonged and the arc energy thereby increased.

The temperature-rises for busbar densities in Fig. 13 are within the British Standard Specification No. 116, namely 30 deg. C. up to and including 2 000 amperes, and 40 deg. C. over 2 000 amperes. I am unaware of any trouble at the juncture of cables and lines directly attributable to the form of excess-voltage dissipation advocated in the paper and elsewhere in my reply. There are many thousands of miles of lines so protected at all recognized pressures up to 66 000 volts in this country. It is notably a standard practice on the North-East Coast. The several causes leading up to the complexity of the balanced protection systems shown in Figs. 32 and 33 are described in the paper. It does not follow that because some exceptional cases warrant this complexity that protective gear is getting more complex than ever. All new efforts must be directed towards simplicity, but reliability and stability have the first claim upon the design.

Fig. 20 is a diagram of busbar layout. It is not to be supposed that it represents the geographical position of the generators. The vertical upward isolation simplifies some of the constructional framework and gearing for large sizes, as shown in Fig. 7, when a crane common to all units is available for raising the removable portion and for transferring it to an inspection bay or to another unit. Moreover, the arrangement eliminates much man-handling, and has a time-saving advantage for massive circuit breakers during the process of erection and maintenance operations. Had Mr. Field taken time to consider the full circumstances the arrangement would not perhaps appear to him "to be a very unsatisfactory layout." At any rate it is one that appears to fulfil the requirements of four of the large power stations in this country, indeed, I believe, in all the power stations in this country which contain any appreciable numbers of circuit breakers of over a million kVA breaking-capacity rating.

Leeds.

Over 50 points worthy of serious attention were raised at this Centre, and I am gratified to receive such appreciation of the principles set out in the paper entirely from engineers competent to speak with authority upon users' experiences. These points include significant comments upon excess-pressure discharge, stability of protection, relative safety of different types of switchgear, duplication of switches and busbars, and the changing-over thereon, breaking-capacity ratings and other important subjects, and I should prefer nothing better than that they should be read as replies to criticisms of those speakers in other places who appear to be less practised in the essentials of satisfactory operating requirements. In consequence of the numerous comments I may perhaps be excused, without risk of being thought negligent, from full discussion of the

subjects already included in the preceding reply, if I deal mainly with the other items.

I understand that Mr. Howard Brown wishes to consider how the principles of protection which have been discussed for alternating currents can be applied to d.c. plant. I believe that the metal-clad enclosure and draw-out gear is suitable and desirable for safety; there are many existing instances of oil-break d.c. metal-clad switchgear for pressures up to 3 000 volts. The circuit-breaking problems are more difficult. The arc energy is greater and more vicious than the corresponding capacity in alternating current. Thus the design of the circuit-breaker portion must be adjusted to suit the more severe conditions. As to discriminating systems of automatic protection, I know of one system of leakage protection which operates on out-of-balance between the current in the positive and negative leads respectively. The reverse-current relay as a discriminating device has no disrepute that I know of, and of course the automatic-control d.c. substation plant is well known and is making considerable advance as an example of automatic and interlocked sequence of operations.

The fuse for potential transformers is a somewhat delicate device at its best; the addition of a separate resistance in circuit with it only adds to the frailty of the whole potential-transformer circuit, but a resistance combined within the fuse itself is a possible solution of the desirability of reducing the amount of short-circuit current which may pass in the event of a fault beyond the fuse. A high-resistance fuse * may also find useful scope as a protective device for comparatively small high-tension feeder circuits, but I would consider the addition of a separate resistance to a small high-tension feeder a risk as it introduces another weak apparatus with its own set of insulators, which are additional parts to maintain and protect.

I think that Mr. Townley's record of experiences on open-type switchgear are of exceptionally notable value and the attention he has drawn in the past, and now repeats, to earthing resistances and the stability of protective systems will have more effect than anything I can say. He gives timely advice in respect to changing over from busbar to busbar; he says "such operations are infrequent and should never be done hurriedly." He speaks of the inefficiency of concrete barriers in isolating an arc once started on switchgear with about 50 000 kW of plant running, and says that extended experience of the behaviour of metal-clad gear under such conditions has yet to be gained. Under no circumstances is it possible for the arc to spread from conductors on panel to panel, for the obvious reason that no metal but earth metal is exposed. An incident is on record where a dead short-circuit was made on metal-clad switchgear due to a constructional mischance when 75 000 kW of plant at the station was running in parallel with a similar amount of plant at other power stations. The entire damage was localized to the faulty switchgear panel and, notwithstanding the violence of the shock to the switch house, not a single consumer or generating plant was interrupted. The only other effect was to burn out an earthing resistance for which one of the generators was afterwards shut down by hand. In contrast with this the Calumet switchgear referred to by Mr. Gregory was reported in the *Electrical World* recently to have caused a complete cessation of supply to parts of Chicago. This was owing to an arc being drawn out and spreading over several panels on one phase; the trouble was even communicated to another phase of the switchgear, notwithstanding the isolated phase construction of the building, and was due to the operating rods becoming damaged. As one speaker said, "the open-type switchgear gives the arc a free ticket." There is available for reference at least 15 years' experience of metal-clad switchgear working in power stations on systems where the plant capacity is equal to or more than that mentioned by Mr. Townley. In every instance of failure known to me the trouble has never spread beyond the part of the panel at the root of the disorder. Mr. Townley asks for the breaking capacity of circuit breakers, but this can only be determined from experience under operating conditions, although I agree that the most useful basis among numerous other characteristics is the volume and strength of tanks and top plates. No further amplification upon the contents of the paper can be more convincing than service experience. Even prearranged tests may mislead because they provide for everything in test-room condition, whereas the greatest stresses in circuit-breaker tanks are to be encountered when the unusual disorder happens, such as accidental sustained arcing. Sheer mechanical reliability is the all-important factor. This can be gauged by inspection and years of service, but cannot be reduced to a formula in the present state of the craft.

* Patent No. 227928 and Prov. Specn. 8686/1925.

The report of Mr. Longman's contribution does not record all that he said, but his criticisms in regard to connecting up protective gear and the need for efficiency in all directions, both as regards the prevention of, as well as the release of, faults are warranted. I am not aware of any breakages attributable to right-angle bends in compound-filled boxes. He draws attention to the single-switch substation equipment (Fig. 28) as a scheme requiring examination from the point of view of reducing switchgear costs. In reply to his question the voltage-balance protection transformer extends so far over the tee as to operate in the event of a failure of the switch fuse.

Mr. Jones also refers to relative efficiencies. It is unusual for manufacturers not to state a breaking capacity, but the actual meaning of the amounts given is frequently obscure.

Mr. Lovell refers to a point mentioned also by Mr. Bridges at Newcastle, viz. the need for some device to close from a distance a switch which controls a doubtful circuit. A device once called an "iron hand" was made for this purpose. This was in the form of as portable weighted lever which could be attached to a switch handle, the weight being tripped over into action closing the switch by a cord pulled from a distance. Other devices for a similar purpose consist of ropes attached over pulleys to obtain the right direction of force in closing a switch directly. These may be some comfort to an operator in an awkward situation, but such safeguards if provided are likely to be missing when most required. The best policy, of course, is to

install switches in all positions which have sufficient rating to withstand closing on a fault without danger to any operator, whether the switch be in a cell or remote-operated ; in any case the safety of the person who happens to be standing by the switch has to be considered, as well as that of the person actually making the operation whether directly or from a distance.

Referring to Fig. 3, the centres of terminals on transformers are sometimes so wide apart as to prevent the use of a direct three-core cable dividing box, otherwise I agree that they would be preferable to the single boxes in the case stated. On the self-balance protection the lead sheath of the cables is insulated from earth at "C" (Fig. 37) and therefore the resultant unbalance due to the fault-current circuit will energize the protecting transformers "D," and thereby operate the protective system.

Mr. Buist's considered communication is rich in practical experience. I have already referred to some of his comments. Regarding his reference to page 436, in order to obtain sensitive trips on certain modifications to Merz-Price protection using current-balancing and biased relays large current transformers have been used. These on open-circuited secondary would give high secondary voltage. For example, a 40-VA transformer when passing 300 amperes (primary) gave a secondary pressure of 1 200 volts on open-circuit. Moreover, transformers of 150 VA have been recommended for longer lines. The corresponding open-circuit voltage would be a source of danger to anyone who might be handling the secondary leads under the impression that they were at low tension. Compared with voltage-balance with single-primary-turn air-gap transformers, a primary current of 300 amperes gives about 12 volts on the secondary, and a momentary maximum of 400 volts is attained only in the event of a short-circuit of 10 000 amperes passing through the primary.

Both Mr. Buist and Mr. Lovell refer to the earthing device shown in Fig. 24. One phase only should be earthed first always. The busbar chamber should be locked off in order to avoid the risk of an operator accidentally earthing the busbar. Sometimes a locking keyway or some such device is added ; this permits the earthing plug only to be applied in the required position. I agree that such precautionary measures are desirable to avoid mistakes. In one instance an operator locked off the correct door, but his superintendent, thinking he had made a mistake, deliberately unlocked the door and inserted the earthing plug in the live contacts.

The following suggestion for "stability ratio" or "efficiency factor" should be read with the stability safety factor figures given in reply to Mr. Leeson.

Voltage-balance feeder protection on the ordinary simple case, an average of	25 : 1
With added apparatus like the diverter relay system ; providing lighter setting when imperative	100 : 1
For generator protection with ordinary current balance and impedance relays	100 : 1
With the addition of bias or diverter relays when lower fault settings are imperative ..	200 : 1

Mr. Buist's contribution to the question of earthing-resistance values is opportune and serves as a more complete reply to Colonel Edgcumbe. The point for their retention, namely, the saving of the alternator, I agree should be met by using a resistance of low ohmic value. This increases the size and consequent cost as shown on the approximate curve, Fig. F, but I believe that the solution, so far as economy is concerned, will be found in the wider use of water resistances.

I trust that the foregoing discussion will lead to a further advance in the science of switchgear engineering and that this section will achieve a future record tending to free the uses of electricity from risk. The fact that electricity is safer than other contemporary power agents, e.g. gas, should not be taken, as it sometimes is, as a narcotic to smooth over the accidents which do occur, however infrequent they may appear to be when considered on the basis of comparative statistics.

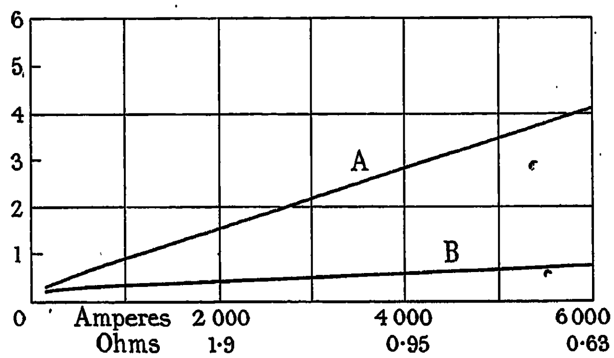


FIG. F.—Approximate cost of earthing resistances on a 6 600-volt system, showing increase in cost with reduction in ohmic resistance.

Curve A.—Costs of grid resistance.
Curve B.—Relative possible cost of liquid resistance.

Bristol.

Mr. Allan's proposal to have accessible change-over links on metal-clad switchgear for the purpose of avoiding the necessity, when repairing a cable, of taking notice of the correct "lay-up" of the phases, has been put into practical application, but it seems to be a refinement hardly justifiable in view of the complication. Moreover, the accessibility of any conductor on switchgear is a source of danger of the kind which metal-clad switchgear in general construction is intended to avoid. In a similar way current transformers have been enclosed in semi-fluid compound so that they are accessible on the removal of a cover. The usual plan, however, is to install current transformers in the first instance of a ratio large enough to anticipate the future demands of the circuit. Another method adopted by some undertakings and, I believe, first employed at Sheffield, is to standardize certain current ratings and when, as in the case of a wattmeter circuit, it is required at the commencement to have a low wattmeter reading, the removable portion of the panel is, for the time being, replaced by one having wattmeter current transformers mounted as an integral part, the whole forming a low-reading wattmeter unit combined with

the circuit breaker. All that is necessary then, when the consumer's load increases, is to withdraw the wattmeter unit and replace it by the standard circuit breaker. This avoids any alterations to connections; it can be very quickly done, and it eliminates any possible danger which might arise from the handling of accessible high-tension conductors. The cost of very high-tension switchgear is certainly prohibitive for small supplies if complete panels with circuit breakers are employed for scattered areas, such as farms and rural districts. The switch-fuse, as illustrated in Fig. 27, is one means adopted to deal economically with such conditions.

Mr. Kernick's point in regard to cable jointing is similar to that referred to by Mr. Allan. In most makes of metal-clad switchgear the cable-testing connections are easily inserted into the orifice sockets which are available when the removable portion is withdrawn. The attachment of such connections to bare conductors on open-type switchgear is frequently a source of danger to the operator owing to the risk of the conductor being inadvertently alive. In metal-clad construction the risk is to some extent reduced, particularly if correct precautions are taken in the design and application of earthing devices, for example, as illustrated in Fig. 24. When making the usual low-tension tests it is preferable first to use the device indicated in Fig. 24 to earth the cable, and then to take the testing connections from the top contact of the switch in place of the earth connection. For high-tension tests, jumper cables to plug into the orifices are substituted for the removable portion. On the whole the risks attendant on making special connections, for testing purposes, to high-tension conductors are reduced by the suitable application of correct metal-clad principles.

Mr. Beasant infers that, whilst much attention is given to a.c. problems, direct current does not have so much as it merits. The metal enclosure of d.c. switchgear is equally desirable, especially on the high voltages now in vogue for railway service. The enclosure and breaking capacity have been discussed in reply to Mr. Howard Brown. I would also refer to the tests recorded by Mr. Collis.* It would be opportune for some up-to-date tests, breaking direct-current short-circuit currents under oil, to be made. This would be a suitable subject for the attention of the British Electrical and Allied Industries Research Association. Circuit breakers of the draw-out oil-break metal-clad type have been used to some extent. Whilst it is true that the demand for those of large breaking capacity is not so general as in the case of alternating-current service, considerable attention is now being paid to the development of high-speed circuit breakers for the protection of converting plant against commutator flashing, which is a step in the direction required by Mr. Beasant.

In reply to Mr. Lewis, breaking capacities are

* Paper read before the South Wales Institute of Engineers, 1911.

obtained from the results of experimental data in breaking short-circuits on alternators, coupled with a close observation of the operation in practical service. The latter is of the greater value in that larger short-circuit fault currents occur accidentally than can be obtained voluntarily by plant at present at the disposal of British manufacturers. As mentioned elsewhere, I know of no infallible formula for calculating the breaking capacity of a circuit breaker from dimensions and characteristics. (See also my reply to Mr. Townley and Mr. Field.)

I agree with Mr. Haigh that of all the circuit-breaker characteristics the strength and dimensions of the enclosure are of primary importance, and possibly he is correct in placing the speed of break next. Most modern circuit breakers have a good kick-off spring release which comes into operation immediately the circuit breaker is tripped. The velocity at the separation of the sparking contacts must be greater when a circuit breaker opens from rest than when opening at the moment of engagement of the sparking tips during a closing operation on a fault. I should not expect this to have an appreciable effect on considerations of breaking capacity. In any case, when closing a switch on a fault there will be a certain lag occurring in the operation of the mechanism which will allow the sparking contacts to travel inwards a short way prior to the reversal of direction. This short distance, however small it is, is enough to allow the sparking contacts to acquire momentum prior to the actual separation. It is possibly true that closing a circuit breaker on a short-circuit is worse than opening on a short-circuit, as there is first the arc disturbance on making contact, and secondly the arc disturbance on breaking contact. This may be a more serious consideration than the velocity at the moment of the contact separation.

Mr. Haslam's remarks are of great importance, particularly with reference to the necessity for the careful determination of the maximum possible short-circuit currents in the several positions in mines. Nowhere has there been such a great progress in the development of large power plant for the application of electricity in mines as in South Wales. For example, there are power stations of large aggregate capacity generating at 3 000 volts practically at the pit heads, and the safety factor in such circumstances cannot be too greatly emphasized. There is a report* existing on the maximum short-circuit currents likely to obtain in several positions in mines.

I confirm also the necessity for careful attention to the relative time function of circuit breakers when two or more circuit breakers of different breaking capacity are connected in one circuit. It is possible by the correct adjustment of definite time-lag to allocate the breaking duty on the heaviest short-circuit currents to the most efficient breaker, which, in many cases, may be preferable to the indiscriminate use of reactances.

* B.E.A.M.A. Technical Committee Report, October 1924.

DISCUSSION ON "SOME RESEARCHES ON THE SAFE USE OF ELECTRICITY IN MINES." *

SHEFFIELD SUB-CENTRE, AT SHEFFIELD, 19 NOVEMBER, 1924.

Professor D. Hay: We have for some years conducted at Sheffield University a standard test for flameproof qualities of commercial electrical apparatus—a test of a limited character based on the earlier work of Thornton, Wheeler and others. Although the conditions of this test do not perhaps go as far as we should like, I feel convinced that this work has served a useful purpose in establishing some kind of limited standard for such apparatus, and this is far better than having no standard at all. It is within our knowledge that the result of the tests has been to cause many modifications in design, and personally I feel satisfied that apparatus designed in accordance with the best recent designs is extremely unlikely to fail in practice. Looking back over the past 15 years, I note that there has been an enormous improvement in the standard of construction, installation and maintenance of electrical apparatus for use underground, and I look for still further advances, following the train of research work such as that described in the present paper, backed up by the efforts of the manufacturers.

Mr. I. C. F. Statham: The conclusions at which the author has arrived are interesting, but before proceeding to apply them in the mine much careful research work is still necessary to ensure that the conditions he lays down are within the safe limits, particularly since the results obtained by Prof. Wheeler are not in consonance with those recorded in the paper. In this connection some results obtained in routine tests of electrical apparatus in the Testing Department of the University of Sheffield also appear to conflict with the author's conclusions. I refer to tests made upon the limiting current permissible with an automatic relay for mining use. In these tests it was found possible to obtain ignitions of firedamp-air mixtures containing between 8·39 and 9·13 per cent of methane with a single-phase current of 1·22 amperes at 100 volts with a frequency of 50. This result was obtained with inductive circuits having a power factor of 0·869, whilst with a practically non-inductive circuit having a power factor of 0·987 the igniting current was 1·60 amperes. It may be remarked that ignition was not obtained every time the circuit was broken, but that a considerable number of "breaks" were necessary in some cases. For example, in one test the operating switch had to be opened and closed 46 times, giving 92 breaks of the relay circuit, before ignition occurred. From these results it would appear that the minimum igniting current values given by the author in Fig. 9 are much too high; they serve to emphasize the necessity for a careful investigation into the question before the conclusions embodied in the paper are applied under the conditions which exist in mines. The author refers to the difficulty of obtaining consistent results in experimental work involving repeated breaks of the circuit, as in the tests to which I have referred. He suggests that the results are vitiated by alteration of the surfaces of the contacts by the development of "hot spots" and the production of irregularities of "spikes" on the contact surfaces by repeated breaks. Whilst agreeing entirely with this, I suggest that such things would occur in practice, and must be taken into account in experimental work having for its object the determination of the limits of safety. If the contacts suffer in this way in the laboratory and reduce the safe current, they will be affected similarly in practice, as they are not taken out, readjusted and polished after each break in order to give consistent break flashes. The author also refers to the influence of the rate of separation of the contacts. This again is difficult, if not impossible, to regulate in practice, but it may be added that, in the tests referred to, the separation of the contacts was electrically controlled so that the rate of separation would be more uniform than when operated by hand. Of greater importance than the above considerations is the fact that with alternating current the result of a single experiment is likely to be misleading, as it is only by the merest chance that the "break" would occur with the current at peak value, and the object of repeated trial was to obtain incidence of current peak and the breaking of the circuit.

Table A gives the more important results of the tests :—

* Paper by Dr. W. M. Thornton (see vol. 62, pp. 481 and 918).

TABLE A.

Test No.	Conditions of tests		Power factor (approx.)	Composition of explosive mixture. Methane, per cent in air	Remarks
	E.M.F.	Current			
	volts	amps.			
161*a*	100·0	1·22	0·869	8·75	Ignition of turbulent mixture after several operations of relay
161*b*	100·0	1·22	0·869	9·13	Ignition of quiescent mixture after 23 operations
161*e*	100·0	1·60	0·987	8·60	Ignition after 46 operations
161*f*	99·1	1·22	0·860	8·39	Ignition after 38 operations

The igniting currents in all cases are considerably below those given in the paper, and in spite of the author's remarks I consider that these results indicate the necessity for a careful inquiry into the whole question before the position can be considered satisfactory from the standpoint of safety, which is the common goal at which we are all aiming.

Mr. H. W. Walker: The tests carried out, and the results shown in the curves, confirm what has been in my mind for quite a long time. In view of Dr. Wheeler's remarks I am rather diffident in mentioning it, but I think it is quite time that d.c. supply was disallowed in the pit altogether. My business is chiefly in connection with breakdowns of underground electrical plant, and from my own fairly wide experience I may say that failures are quite 50 per cent higher with d.c. than with a.c. plant, hence this is a danger additional to those indicated in the paper. I should very much like to hear the author's opinion regarding pit lighting with 25-volt 150-cycle supply, which I think would be satisfactory and safe values, and how this is to be carried out. In my opinion lighting is not required along the whole distance of many pit roads, but chiefly at the coal face, in haulage and pump houses; whilst at road junctions as well as at the shaft bottom it is essential. As one must consider the voltage-drop and cost of wiring to install lights at an a.c. voltage of 25, with a frequency of 150 cycles, I consider that the most satisfactory and safe method would be to use small motor-generators which could be installed in a haulage or pump house in the district in which lights are required. These small machines can be constructed in flameproof cases, and can be run off the normal power supply, whatever it may be, and would be under the control of the regular haulage or pump attendant. The capacity of the generator need be only about 1 kW in many cases, and in such instances it would be impossible to attain a dangerous current, even in the event of a short-circuit.

Mr. F. O. Hunt: I should like to draw the attention of the younger and Student members to the importance of the many side-line investigations of this research as throwing light upon the mechanism of gaseous combinations. On the question of the importance of ionization in bringing about combination I would suggest that the extra activity of nascent gases so long known to chemists is probably really a matter of the greater number of free ions present in gases under such conditions.

Mr. L. H. Crowther: I should be interested to know the approximate resistance necessary for the shunted signalling bell. I assume it is wound non-inductively. Regarding the question of a.c. versus d.c. systems of supply, I can confirm the author's statement from my own experience in a steelworks with which I am connected. The plant and distributing system are fairly evenly divided into a.c. and d.c. groups, and although installed at approximately the same time the troubles due to insulation breakdowns on the d.c. system are quite appreciably greater than those experienced on the a.c. system. I was interested to see the suggested method for ensuring a low-resistance earth, and I believe that the author gave a figure representing the resistance of the earth. How was that figure obtained and what distance apart were the two points between which the resistance was measured? The nature of the intervening ground would no doubt affect the value to a greater or less extent.

Prof. R. V. Wheeler: I understand that the inductance of the circuit in the experiments recorded in Fig. 5 was low and that perhaps accounts for the difference between the author's results and my own. Using direct current at 35 volts with 0·095 henry inductance, and alternating current at 25 volts (R.M.S. value, 35·3 volts crest value) with 0·098 henry inductance, 50 cycles per second, I have been unable to find any material difference in the igniting current required for mixtures of methane and air by break-flashes produced mechanically at platinum contacts. I give below some typical results:—

	Methane, per cent	6·15	7·10	7·60	8·00	8·50	9·00	9·60	10·20	10·90
Igniting current, in amps.	Direct	0·43	0·30	0·26	0·24	0·24	0·25	0·28	0·32	0·42
	Alternating (crest values)	0·49	0·36	0·30	0·26	0·24	0·25	0·26	0·30	0·44

Since I had not the facilities to experiment with alternating current at a higher frequency than 50 I asked Mr. J. D. Morgan, of the Marks and Clerk Laboratory, if he could do so. He describes his experiments in a letter to me as follows: " A small alternator giving a good sine wave was arranged in a circuit containing the ignition apparatus, an air-core inductance coil, a resistance and a hot-wire ammeter. Provision was made for including in series with the circuit a small accumulator as a source of direct current. In the direct-current experiments the alternator rotor was fixed in the position of maximum inductance, and the current from the battery was adjusted until the spark obtained on breaking the circuit was able to ignite the gas. Subsequently the battery was removed from the circuit and current was generated by the alternator, the resistance of the circuit remaining the same. The excitation of the alternator was varied until the least igniting spark was obtained. The results of experiments with an 8·5 per cent methane-air mixture were as follows:—

	Igniting current, in amperes		
	R.M.S. value		Peak value
Direct current	—	0·415	—
Alternating current, 68 cycles	0·285	—	0·41
Alternating current, 200 cycles	0·300	—	0·42

It will be apparent that the results for alternating and direct current are practically the same."

Mr. H. E. Yerbury: As I understand the subject matter, the author's researches and conclusions lie in the application to and safety for mining work of an alternating current of low voltage and comparatively high frequency, as compared with a direct current. No theory can be held to be entirely satisfactory unless it can be justified by actual demonstrations. I believe that phenomena are determined by conditions; therefore if the conditions are altered different phenomena are manifested. I should be glad if the author would indicate what means or what type of apparatus or machine he would recommend to furnish this a.c. energy, which presumably should be at unity power factor with no stored electromagnetic energy anywhere. It is common knowledge that the intensity of a spark or switch or other contact is far greater with a low power factor, and conversely the absence of self-induction minimizes the intensity of any spark. Are we to understand that if the conditions of any circuit are such as to manifest self-induction, the results would be different and perhaps dangerous as compared with the conditions which existed at the time the tests were taken?

Professor W. M. Thornton (*in reply*): I am glad to hear Prof. Hay's remarks on the improvement of electrical apparatus underground. My own feeling is that the next and very difficult step is to secure a state of maintenance equal to the quality of the installation.

Mr. Statham's results are interesting as showing that he, in common I believe with Dr. Wheeler and Mr. Morgan, has worked with a type of mechanical make-and-break that might have been specially designed to mask all difference between direct- and alternating-current sparks. We found 15 years ago that a contact made so that the surfaces were scraped open at break was useless as a means of discriminating between one set of electrical conditions and another. The circuit constants, and even voltage, are then of less influence on the igniting properties of the spark than the physical or mechanical conditions of the break. A scraping contact, made by a thin spring pressing against a pole and at the point of break making a sharp flick, gives to the spark a shortness of duration comparable with the period of an alternation, so that so far as break is concerned there is no difference between the time of extinction of the two, nor has the rapidity of alternation of the current then any chance of affecting the result. Such a condition is never met in practice; breaks of cables or contacts do not occur between thin steel or brass springs. There is the further objection to mechanical breaks of this kind that the current density at the point of break is very high, and that the thermal capacity of the metal behind the break has no time to influence the spark. Everything therefore is equalized. For this reason we abandoned after a few months' research the method which appears to find most favour with these investigators.

Mechanical breaks are always troublesome. If an electromagnetic break is used, the current must be shut off before make, or the contacts chatter and ignition can occur at make. Unless a mechanical "knock-off" device is used the break is relatively slow at the moment of opening the contacts, and this again tends to equalize the effects of direct and alternating current, for the spark in an alternating-current circuit then lasts many periods and is equivalent to a direct current. In practice, breaks most usually occur, as I have found by many trials, by a sharp straight pull-out of conductors, not a slow separation or the flick of a spring. For this reason and others, in the course of a long series of trials I gave up mechanical breaks as less reliable than hand control. I found that two round conductors crossed at right angles and separated either by hand with a quick turn or by an eccentric motion having this effect, gave entirely consistent results that could be repeated within 1 per cent at the critical values, and that method has been followed consistently for some years. The fact that these investigators have failed to obtain any difference between direct and alternating current shows that their method was not suitable for discriminating between them. For in the demonstration (at the meeting) I showed that 0·7 ampere direct current gave the same ignition as over 7 amperes alternating current, the circuits, voltages and mode of break being the same. That there is a distinct difference in practice between direct- and alternating-current working in favour of the latter is borne out by Mr. Walker's remarks, and many experienced colliery electrical engineers will agree with him. I believe that small low-voltage machines could be installed, as he says, in a haulage or pump house, and supply a district with light under conditions of safety and shock much in advance of anything now in use. A method of obtaining frequencies of 150 has now been found which makes such a scheme practicable. It is to use an induction motor with specially wound poles as a frequency changer and transformer, giving at the same time a rise of frequency from, say, 50 to 150 and a fall of voltage to any desired value at the slip-rings.

In reply to Mr. Crowther, I would refer him for full particulars on direct-current bells to a paper by Dr. Wheeler and myself on "Bare Wire Signalling." Alternating-current bells are, I believe, now under investigation here.

Mr. Hunt calls attention to the many interesting scientific side-lines of this work. There is a great field for younger investigators, but it is difficult to find the combination of physical, chemical and engineering experience necessary to obtain results in the time a young or post-graduate student has available. For example, it is now practically certain that all the phenomena of spark ignition arise from the energizing of molecules of one of the two combining gases, probably in part both, by electromagnetic radiation from the spark. This introduces the large question of quantum-action, and work on these lines leads to interesting results, but to find the ultimate physical reason for the differences between direct- and alternating-current break-sparks, impulsive and condenser discharge-sparks, based on detailed experimental research on quantum lines is a great and difficult research, and there is more pressing work to hand in consolidating the advance which has been made during the last 15 years in the improvement of electrical conditions underground.

PROCEEDINGS OF THE INSTITUTION.

46TH MEETING OF THE WIRELESS SECTION, 6 MAY, 1925.

(Held in the Institution Lecture Theatre.)

Mr. E. H. Shaughnessy, O.B.E., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 1st April, 1925, were taken as read and were confirmed and signed.

The Chairman announced that the following nominations had been made by the Wireless Section Committee to fill the vacancies which would occur on the Committee on the 30th September, 1925 :—

Chairman : Major B. Binyon, O.B.E., M.A.

Members of Committee : Mr. P. R. Coursey, B.Sc., Mr. L. B. Turner, M.A., Captain H. J. Round, M.C., and Mr. E. H. Shaughnessy, O.B.E.

A paper by Captain H. J. Round, M.C., Member, and Messrs. T. L. Eckersley, K. Tremellen and F. C. Lunnon, entitled " Report on Measurements made on Signal Strength at Great Distances during 1922 and 1923 by an Expedition sent to Australia " (see page 933), was read and discussed.

On the motion of the Chairman a vote of thanks to the authors was carried with acclamation, and the meeting terminated at 7.42 p.m.

53RD ANNUAL GENERAL MEETING, 7 MAY, 1925.

(Held in the Institution Lecture Theatre.)

Mr. W. B. Woodhouse, President, took the chair at 6 p.m.

The notice convening the meeting was taken as read. The minutes of the Ordinary Meeting held on the 23rd April, 1925, were also taken as read and were confirmed and signed.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

Messrs. G. A. Gardner and A. W. Marshall were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the result of the ballot was declared as follows :—

ELECTIONS.

Associate Members.

Bentley, John.
Church, George Henry.
Davidson, Ward Follett, M.Sc.
Duguid, David Robertson.
Gardner, Alfred Charles.
Green, Ernest Hedley R.
Hill, Thomas.
Kamm, Leo.
Lay, Francis Arthur.
McDermott, John.
Payn, Harry.
Walker, Vernon.
Ward, Cyril Alfred.

Graduates.

Bagchi, Kamakhija Prasad.
Bancroft, Herbert Douglas.
Blake, George Thomas.
Cain, Sidney John.
Clissold, William Cornelius.
Davies, Thomas Edward.
Humphreys, Herbert Frederick.
Lewis, Llewellyn Brigstocke.
Magrow, Gordon Emm.
Shepherd, David Kennedy.
Sundar, Padma Malla, B.Sc.
Walker, John.

Students.

Adney, William Stanley.
Ashdown, Herbert Arthur, B.Sc.(Eng.).
Beale, Shirley John M.
Beney, William Harry.
Birtwistle, Marshall.
Bothamley, Henry Valentine.
Clements, Vernon Arthur H.
Cooke, Edward Maurice.
Davis, John James.
Drew, Denis Arthur, B.Sc.(Eng.).
Drummond, Charles Walter B.
East, Norman.
Edmunds, Frederick William.
Edsall, Eric Arthur M.
Edwards, Herbert Carlton.
Gray, George William E.
Harmer, Leslie Brooke.
Harvey, Leonard.
Hebblethwaite, Arthur William.
Herwald, Nehemiah.
Kantebet, Shankar Rao, B.A.
Keens, John Ernest A.
Lambert, Douglas Edward.
Lee, Kent D.
McLean, Archibald Legget.
Morfitt, George Ernest.
Prior, Frederick Ernest.
Prowse, John Albert.
Ridgeway, John Whinfrey.
Roberts, Albert Victor.
Savage, John Henry.
Scott, James Stevenson.
Shepherd, Cyril.
Smith, Edwin Marshall.
Southin, Charles Frederick.
Stanley, Thomas Edward.
Tordoff, William Humphreys.
Tsao, Tsen-Cha.
Tyack, Francis George.
Verity, Ronald Meysey.
White, Thomas Sydney.
Wigan, James William.
Wilde, William Norman.
Willis, Leslie Robert K.
Winch, Richard Frederick.

TRANSFERS.

Associate Member to Member.

Bridger, William, B.Sc.(Eng.).
Davies, George Frederick.
Hunter, Egerton Baird.
Hurford, George.
Leadbeater, James.
Parkinson, Frank.

Graduate to Associate Member.

Akehurst, Arthur Gerald.
Blaquiere, Henry Arnold.
Campbell, John James B., B.Sc.
Carter, Arthur.
Chatterjee, Sarat Kumar, B.Sc.(Eng.).
Gray, Ronald, M.C.
Leyland, Arthur James, B.Sc.Tech.
Mundy, Sydney George.
Wales, William Arvon.
Wicks, Percy, B.Sc.

Student to Associate Member.

Butler, Percy, B.Sc.
Douglas, John, B.Sc.
Lee, Herbert Cleave.
Turner, Victor Robert.

Associate to Associate Member.

Grier, John James.
Webber, Wallace James.

Student to Graduate.

Alford, Ferderick Albert H.
Angier, John Ralph T.
Barrow, Lucien Leacock.
Bygott, Hugh Cecil.
Dickinson, Richard Heath.
Gibbs, William Reginald.
Newman, Claude.
Redfearn, Charles Herbert.
Rhodes, Arnold, B.Sc.Tech.
Wells, Ewart Henry, Ph.D., M.Sc.

The following lists of donations were taken as read and the thanks of the meeting were accorded to the donors :—

Library : Air Ministry; W. Aitken; C. Andry; Astronomer Royal; A. Bachellery; Professor F. Bacon, M.A.; F. G. C. Baldwin; Messrs. E. Benn, Ltd.; British Engineering Standards Association; British Engineers' Association (Incorporated); Comité International des Tables Annuelles de Chimie, de Physique et de Technologie; General Assembly, Pennsylvania; F. M. Denton; F. Deulicke; Electricity Commissioners; Government Inter-Departmental Standardization Committee; Sir Robert Hadfield, Bart., F.R.S.; K. Hedges; High Commissioner for Canada; W. S. Ibbetson; Imperial College of Science and Technology; Institution of Engineers, Australia; H. M. Lacey; H. I. Lewenz; Librairie Vuibert; Library Association; Messrs. P. Lund, Humphries & Co., Ltd.; "Locomotive, Railway Carriage and Wagon Review"; Messrs. Merz and McLellan; W. M. Mordey; J. S. C. Morris (Exor. M. Hughes); I. Namari; Lieut.-Colonel W. A. J. O'Meara, C.M.G., R.E.; Patent Office Library; Director of Posts and Telegraphs, India; Chief Electrical Engineer, Public Works Department, New Zealand; Messrs. S. Rentell & Co., Ltd.; Royal Society of Arts; Director, Royal Technical College, Glasgow; Director, Science Museum; Chief Experimental Officer, Signals Experimental Establishment, Woolwich; Messrs. E. & F. N. Spon, Ltd.; C. L. E. Stewart; S. A. Stigant; Syndics of the Cambridge University Press; Under-Secretary for Mines; University Tutorial Press, Ltd.; and Messrs. H. F. & G. Witherby.

Benevolent Fund : (See list of Donations on page 519.)

The President, after reviewing the work of the session, moved "That the Annual Report of the Council for the year 1924–25 * as presented be received and adopted."

* See page 571.

The resolution was seconded by **Mr. A. H. Allen,** and comments and suggestions were made by **Mr. F. W. Purse, Mr. L. W. Phillips, Mr. D. G. Hurlbatt,** and **Mr. P. M. Baker,** to which the President replied.

The Report was then unanimously adopted.

The chair was then vacated by the President (who had to leave the meeting in order to attend another engagement) and taken by **Mr. S. Evershed,** Vice-President.

The Chairman : I now call upon the Honorary Treasurer to move a resolution in regard to the Statement of Accounts and Balance Sheet.*

Mr. P. D. Tuckett (Hon. Treasurer) : I am happy to be able to congratulate the members on what I feel sure they will regard as a very satisfactory statement. It will be seen that in spite of the reduction in the subscriptions which came into force on the 1st January, 1924, the income for the year is only £2 094 less than in the previous year. On the other side of the Revenue Account the expenditure shows an increase of £1 090, excluding the reserve provisions at the foot of the statement. That increase of £1 090 is mainly attributable to one or two special items. Under the heading of "Institution Building" there is an increase of £900 in the amount of £1 500 reserved for Repairs. As you will see from the Balance Sheet that we have had to write off £855 against the Repairs Suspense Account, whilst the still larger amount of £1 297 was written off in the previous year, it was felt that an annual provision of £600 was hardly adequate and that it would be wise to increase it, at any rate for a time, to the larger figure of £1 500. This should result in restoring the somewhat depleted Repairs Suspense Account and should enable each year's repairs to be met by a charge against this Account, since it is most unlikely that they will on the average exceed £1 500. In addition to this increased Repairs provision, we have had to incur a very exceptional expenditure of £1 615 in providing new boilers, etc.; and there are several other small increases, including one of £394 in the amount of the Special Grants made by the Council. As a set-off against these increases you will be glad to see that we received an additional rental of £2 067 from our tenants in this building, besides saving £1 093 in the net cost of the *Journal*, thanks to increased sales and advertisements. *Science Abstracts* also, which used to make a substantial call on our resources, cost us only £68. It is true that this exceeds the previous year's figure by £41, but I think you will agree that it is still quite a moderate figure and one on which the Committee responsible for the publication are entitled to be congratulated. Of the special items at the foot of the Account, it will be seen that this year only £3 500 has been carried to the Reserve Fund for contingencies and mortgage redemption, as against £4 500 a year ago, whilst £1 310 less has been expended on furniture, fittings and apparatus. The balance of £2 925 carried to the General Fund in the Balance Sheet is thus only £1 032 smaller than the amount carried down a year ago. As stated in the Report, the Assets taken at their book values,

* See page 580.

after deducting the Liabilities, now amount to £133 016, an improvement of £7 616 over the corresponding figure a year ago. It is gratifying to have this proof of the strong financial position in which the Institution now stands, and I believe that the members have every reason to feel satisfied with it and with the prospects for the current year, although there is one heavy item of expenditure which will adversely affect this year's Accounts, and that is the re-wiring of this building. It has been found that the wiring is worn out, and the Council have decided that it must be renewed at an estimated cost of about £3 000. In addition, this is the year of the quinquennial valuation for rating purposes, and the chances are that our rates will be substantially increased. So that although I do not anticipate any marked reduction in the amount of the balance which we shall be able to carry to the General Fund at the end of the year, I doubt whether it will exceed the balance shown this year, and it is quite possible that it may be somewhat smaller. With these few remarks I beg to move : "That the Statement of Accounts and the Balance Sheet for the year ended 31st December, 1924, as presented be received and adopted."

The resolution was seconded by **Mr. J. E. Kingsbury** and after the Chairman had replied to comments by **Mr. D. G. Hurlbatt, Mr. F. W. Purse** and **Mr. E. W. Moss**, was unanimously adopted.

The following resolution, moved by **Mr. Ll. B. Atkinson** and seconded by **Mr. P. M. Baker**, was carried with acclamation : "That the best thanks of the Institution be accorded to the following officers for their valuable services during the past year: (*a*) The Hon. Secretaries of the Local Centres and Local Hon. Secretaries abroad, and (*b*) the Hon. Treasurer (Mr. P. D. Tuckett)."

Mr. A. F. Harmer then moved "That Messrs. Allen, Attfield & Co., be appointed Auditors for the year 1925–26."

The resolution was seconded by **Mr. W. Nairn** and carried unanimously.

The meeting terminated at 6.55 p.m.

47TH MEETING OF THE WIRELESS SECTION, 3 JUNE, 1925.

(Held in the Institution Lecture Theatre.)

Admiral of the Fleet Sir H. B. Jackson, R.N., G.C.B., K.C.V.O., F.R.S., took the chair at 6 p.m. in the absence of Mr. E. H. Shaughnessy, O.B.E., Chairman of the Section.

The minutes of the meeting of the Wireless Section held on the 6th May, 1925, were taken as read and were confirmed and signed.

The Chairman reported that, no other nominations having been received to fill the vacancies which would occur on the Committee on the 30th September, 1925, the Committee's nominees* had been duly elected.

A paper by Dr. R. L. Smith-Rose, M.Sc., Member, entitled "The Effect of Wave Damping in Radio Direction-Finding" (see page 923), was read and discusssd.

On the motion of the Chairman a hearty vote of thanks was accorded to the author, and the meeting terminated at 7.25 p.m.

* See Proceedings of the meeting of the Wireless Section held on the 6th May, 1925 (page 1041).

INSTITUTION NOTES.

List of Members.

A new List of Members (corrected to the 1st September, 1925) is in preparation and members wishing to receive a copy should apply to the Secretary.

International Conference on E.H.T. Lines.

It is proposed, subject to there being a sufficient demand, to publish an English edition (in two volumes of about 1 100 pages each) of the papers read at the International Conference on E.H.T. Lines held in Paris from the 16th to the 25th June, 1925. The volumes will also contain a report of the discussions.

If the demand reaches 400 copies, the price will be £4 for the two volumes, but in the event of 800 copies being subscribed for, the price will be £2 10s.

In order that an early decision may be arrived at as to whether to publish an English edition, those wishing to subscribe for copies are requested to inform without delay

Monsieur Tribot Laspière,
Union des Syndicats de l'Électricité,
25, Boulevard Malesherbes,
Paris,

of the number of copies they will require.

A French edition of the papers and discussions will also be published, provided not less than 1 000 sets are subscribed for. The price will be 200 francs per set, but after the 1st November, 1925, the price will be increased to 250 francs. Orders for the French edition should also be sent to M. Tribot Laspière at the address given above.

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 August–25 September, 1925 :—

	£	s.	d.
Anonymous		1	0
Baker, A. C. (Birmingham)		10	6*
Bentley, J. C. (Manchester)		5	0
Brown, William (Leeds)		10	0
Conly, W. P. (Birmingham)		2	6*
Gazard, W. A. (Birmingham)		5	0*
Glen, J. B. (North Shields)		5	0
Haley, W. E. (Shipley)		5	0
Hamilton, C. (Shanghai)		5	0
Hunter, E. I. (Manchester)		2	6
Irish Centre	3	11	0
Jackson, F. S. (Halifax)		15	6
Leigh, J. H. (Manchester)		5	0
McKinnon, E. C. (Stockport)	1	1	0
Moscrip, W. R. (London)		5	0
Porte, F. C. (Cork)	1	1	0
Reynolds, E. A. (Birmingham)		5	0*
Roberts, A. J. (London)		5	0
Stewart, A. (Teddington)	1	1	0
Ward, W. (Hull)		5	0

* Annual subscriptions.

Accessions to the Reference Library.

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Vol. 1 *has title* Continuous current circuits and machinery.

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MOYER, J. A., and WOSTREL, J. F. Practical radio, including the testing of radio sets. sm. 8vo. 256 pp. *New York*, 1924

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PAINTON, E. T. Mechanical design of overhead electrical transmission lines. 8vo. 282 pp. *London*, 1925

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THE USE OF THE CATHODE-RAY TUBE AS A WATTMETER AND PHASE-DIFFERENCE MEASURER FOR HIGH-FREQUENCY ELECTRIC CURRENTS.*

By J. A. FLEMING, D.Sc., F.R.S., Honorary Member.

(*Paper received 9th December*, 1924.)

SUMMARY.

This paper contains an account of the manner in which a cathode-ray tube can be employed to measure high-frequency power, i.e. as a wattmeter, by the delineation and measurement of the ellipse formed on a phosphorescent screen by a cathode-ray spot, which is oscillated in two directions at right angles by the current and voltage of the circuit under test.

Now that the cathode-ray oscillograph with oxide-coated hot cathode has been made into an instrument capable of being operated by a few hundred volts furnished by dry cells in place of the troublesome electrostatic machine, due to the research department of the Western Electric Company, it has become a valuable appliance for high-frequency measurements. The following theorem, which has not previously been given, may therefore be found useful in connection with the use of the cathode-ray oscillograph as a wattmeter for high-frequency circuits.

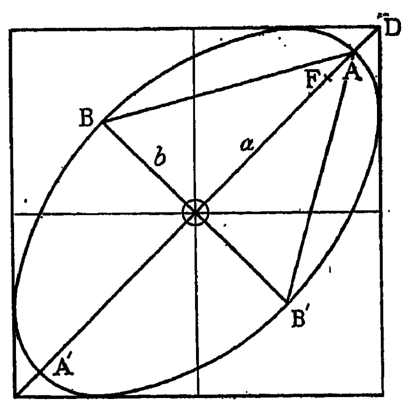
In this form of tube the cathode particles are projected along the tube and pass between two pairs of parallel deflecting plates, set with their planes at right angles. By giving to one or both of these pairs of plates a difference of potential the cathode ray, and therefore the green spot on the phosphorescent screen, can be deflected in one or both of two directions which are at right angles to each other.

Suppose one pair of plates connected to the terminals of a non-inductive resistance inserted in the circuit of a high-frequency current. Then the spot will be expanded into a green line perpendicular to the plane of the deflecting plates, and this is due to the motion of the cathode spot backwards and forwards with sinusoidal motion and amplitude proportional to the maximum value of the current. If, then, the other pair of plates are similarly connected to the ends of a resistance in another circuit in which there is a second high-frequency current of the same frequency and with a constant difference of phase, the cathode spot will be deflected in a direction at right angles to that of the other motion, and if the phase difference of the two remains constant the resultant motion will be a closed curve. By various devices, which it is unnecessary to specify, we can give to the cathode spot two sinusoidal motions at right angles, and make these motions have equal amplitudes and constant difference of phase, one due to the current in a circuit and the other to the potential difference causing that current. The form of the closed curve then described by the cathode spot, which is an ellipse, enables us to find the phase difference of the two currents, or of the current and voltage creating the two motions.

Thus if we assume one of the rectangular displacements to be expressed by the equation $x = A \sin \omega t$ and the other by $y = A \sin (\omega t + \theta)$, where A is the amplitude and θ the phase difference, it is easy to see that by the elimination of the time variable ωt we have the equation to the path of the cathode spot on the screen, which is

$$x^2 + y^2 - 2xy \cos \theta = A^2 \sin^2 \theta$$

This is the equation to an ellipse which is circumscribed by a square of side $2A$ and semi-diagonal OD $= A\sqrt{2}$. The major axis of this ellipse coincides in direction with the diagonal of the circumscribing square (see Figure).



To find the lengths of the semi-axes, major (a) and minor (b), put $x = y$ and $x\sqrt{2} = a$ in the above equation, and we obtain

$$a = (A\sqrt{2}) \cos (\tfrac{1}{2}\theta)$$

To obtain b, put $y = -x$ and $x\sqrt{2} = b$, and then

$$b = (A\sqrt{2}) \sin (\tfrac{1}{2}\theta)$$

Accordingly $b/a = \tan (\tfrac{1}{2}\theta)$ and $\theta = 2 \text{ arc tan } (b/a)$. Hence if the cathode spot is actuated by two sinusoidal motions at right angles to each other which have equal amplitude and phase difference θ, the cathode spot will delineate an ellipse and this curve can be photographed or drawn with the camera lucida from the green-line curve seen on the phosphorescent screen.

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To find the phase difference θ, all we have to do is to determine and draw the major and minor axes of this ellipse.

On the minor axis BB′ describe an isosceles triangle BAB′ with its apex at the extremity A of the major axis. Then the angle BAB′ ($= \theta$) is the phase difference of the two periodic motions. If F is one of the foci of this ellipse, then, if $OF = f$, we know that $a^2 - b^2 = f^2$, and hence that $f^2 = 2A^2 \cos \theta$. But $A\sqrt{2}$ is the length of the semi-diagonal OD of the circumscribing square, and hence the power factor, $\cos \theta$, is equal to $(OF)^2/(OD)^2$.

If then we have the path of the cathode spot drawn or photographed we can easily find the foci of this ellipse and draw the circumscribing square, thereby finding θ and $\cos \theta$ as above explained.

Assuming that one motion of the cathode spot is due to a high-frequency alternating current and the other rectangular motion to the voltage producing that current, we can thus find the phase difference and therefore the power taken up in the circuit. The cathode-ray tube thus becomes a high-frequency wattmeter much more easy to manage than any electrostatic form of wattmeter of the Kelvin-quadrant type.

THE CATHODE-RAY OSCILLOGRAPH.*

By A. B. Wood, D.Sc.

(*Paper received 17th September, 1924.*)

SUMMARY.

The paper draws attention to three commercial forms of cathode-ray oscillograph which may be employed in the study of very high-frequency alternating or impulsive electrical phenomena.

The behaviour of a stream of cathode rays in electrostatic and magnetic fields is first dealt with, and the penetrating power of cathode rays through matter is considered in relation to the velocity of the rays. Making use of this fundamental information, simple relations are obtained expressing the current and voltage sensitivities of cathode-ray oscillographs, the important features to be observed in the design of these instruments being indicated. The question of photographic sensitivity is also discussed, and calculations are made of the relative photographic effects produced by cathode rays of different velocities. It is shown that ordinary photographic plates or films are, in general, unsuitable for recording by means of low-velocity cathode rays. For this purpose a certain type of plate known as the Schumann plate, which is very rich in silver bromide relative to gelatine, is recommended for recording at very high speeds.

The principal features of three oscillographs, viz. the Dufour, the Western Electric and the author's, are described and a comparison is made of their relative advantages.

A few of the numerous applications of cathode-ray oscillographs are indicated, and a number of records made by each of the three types are reproduced in illustration.

I. INTRODUCTION.

The cathode-ray oscillograph, a recent development of the Braun tube, is rapidly becoming a necessity in many branches of physics and electrical engineering. During the past few years this form of oscillograph has emerged from the experimental stage and the commercial forms now produced may be looked upon as reliable laboratory instruments. For low-frequency alternating-current work the Duddell and Einthoven types of oscillograph fulfil a very useful purpose, but they fail entirely at very high frequencies (10 000 periods per sec. and upwards). Even at frequencies above 1 000 these oscillographs require the use of troublesome correction factors involving the relation between the natural period of the moving element and the impressed frequency.

The cathode-ray oscillograph, on the other hand, is equally sensitive at all frequencies from zero to the highest frequency of oscillation which is conceivable in an electrical circuit; for the cathode ray is, after all, an electron in motion and can therefore execute any oscillation which can be performed by other electrons oscillating in electrical circuits. On general grounds, therefore, it would seem reasonable to suppose that the cathode-ray oscillograph must ultimately supersede any other form of oscillograph which involves a moving element having inertia, like the mirror and strips of the Duddell galvanometer, or the fibre of the Einthoven instrument.

It is the object of this paper to draw attention to this new form of oscillograph which has already proved its worth in recording oscillations of the order 10^7 periods per sec. and in recording impulsive phenomena of extremely short duration. It is proposed also to deal with some of the fundamental features of the design of such oscillographs and to refer in particular to three types at present in use.

II. SOME PROPERTIES OF CATHODE RAYS.

The methods of producing a beam of cathode rays in a highly evacuated tube are dealt with in most

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textbooks of electricity and require little more than a brief mention here. These rays consist essentially of electrons accelerated in a vacuum tube by application of suitable potentials, the velocity of the rays being a simple function of the potential difference applied. The electrons may be produced by collision with the molecules of gas in the tube or, alternatively, by means of a heated filament. In the latter case, which is generally employed in practice, the tube may be very highly evacuated and low voltages employed to accelerate the electrons. In the former case, where ions are produced by collision, a trace of gas is left in the vacuum tube and high voltages must be employed to excite a cathode stream of sufficient intensity. On general grounds it is usually considered preferable to employ a hot filament cathode, the alternative method, used in the original Braun tube, being somewhat unreliable and fickle. Before dealing with the design of cathode-ray oscillographs, it is essential to examine the behaviour of cathode rays in electrostatic and electromagnetic fields and to obtain an idea of the photographic action of rays of different speeds.

(*a*) *Charge, mass and velocity of cathode rays.*—The classical experiments of Sir J. J. Thomson in determining the values of e, e/m, and v for cathode rays * are well known. As we are only concerned here with the actual values of these quantities, we shall refer merely to the results of the latest determinations by more refined methods.† The following values may be accepted as reliable :—

$e = 1\cdot59 \times 10^{-20}$ electromagnetic units.
$e/m = 1\cdot772 \times 10^{7}$ electromagnetic units (for low-velocity rays).
whence $m = 10^{-27}$ gramme approximately.

The mass of a cathode particle is therefore entirely negligible when compared with the mass of the finest silvered quartz fibre obtainable (0·002 mm diameter), viz. 10^{-7} gramme per cm length.

The velocity v of the cathode ray is of course a function of the accelerating voltage V, and the following expression is a fairly accurate representation of the relation between them :—

$$v = 5\cdot95\sqrt{(V)} \times 10^{7} \text{ cm per second‡} \qquad (1)$$

where V is expressed in volts.

The kinetic energy of the cathode rays is therefore proportional to the accelerating voltage V.

(*b*) *Deflection in electrostatic fields.*—We shall consider only the simple case where the beam of cathode rays passes with uniform velocity v between two parallel plates in a direction normal to the lines of electric force (see Fig. 1). In this figure P_1P_1 and P_2P_2 represent the parallel plates of length λ at a distance d apart. A potential difference of E units is applied to the plates, and the stream of cathode rays travels initially along the line OX. In their passage through the electrostatic field, however, the negatively charged particles are deflected towards the positively charged plate. At the point of emergence from the plates the rays have been deflected a distance y_1 from the line OX and are travelling along a path inclined at an angle α to this line.

If m is the mass of the cathode particle and e its charge, then the force displacing the particle in the direction of the Y axis is $e(E/d)$ and $m(d^2y/dt^2) = eE/d$. On integrating we have

$$\frac{dy}{dt} = \frac{eE}{md}t + C_1$$

and

$$y = \frac{eE}{2md}t^2 + C_1t + C_2$$

The constants of integration vanish, since dy/dt and y are both zero when $t = 0$.

Writing $t = x/v$, we have

$$\frac{dy}{dt} = \frac{eE}{md}\cdot\frac{x}{v}$$

and

$$y = \frac{eE}{2md}\cdot\frac{x^2}{v^2}$$

That is, the rays travel along a parabolic path between the deflecting plates, the displacement y being at any instant proportional to the square of the distance x travelled by the rays from the point O.

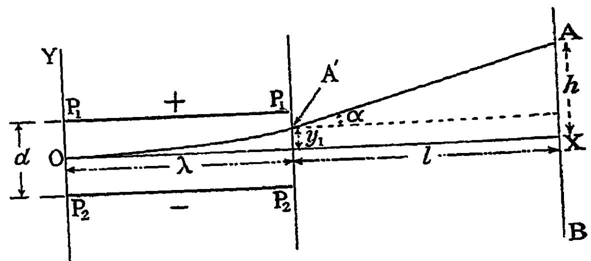


FIG. 1.

At the point where the rays emerge from the parallel plates $x = \lambda$, and the direction of the rays makes an angle α with OX at a point A′ displaced a distance y_1 at right angles to OX. After leaving the deflecting plates the rays travel along a straight line A′A until they strike the plane AB at A, the total displacement along the Y axis being AX $= h$, where $h = y_1 + l\tan\alpha$, l being the distance traversed by the rays after leaving the deflecting plates.

$$\tan\alpha = dy/dx, \quad \text{where } x = \lambda,$$

$$\therefore \tan\alpha = \frac{1}{v}\cdot\frac{dy}{dt} = \frac{eE}{md}\cdot\frac{t}{v} = \frac{eE}{md}\cdot\frac{\lambda}{v^2}$$

whence

$$h = \frac{eE\lambda^2}{2mdv^2} + \frac{eE\lambda l}{mdv^2}$$

i.e.

$$= \frac{e}{m}\cdot\frac{E}{v^2}\cdot\frac{\lambda}{d}(l + \tfrac{1}{2}\lambda) \qquad (2)$$

This relation giving the final displacement of the cathode rays is of fundamental importance in the design of a cathode-ray oscillograph and will be referred to later.

(*c*) *Deflection in magnetic fields.*—Here again we shall deal only with the simple case where the stream of cathode rays travels along a path at right angles

* See J. J. THOMSON: "Conduction of Electricity Through Gases."
† See MILLIKAN: "The Electron."
‡ See G. W. C. KAYE: "X-rays."

to the lines of magnetic force. The deflection produced under these conditions will be at right angles to the path of the rays and to the magnetic field. Thus, in Fig. 1, $P_1P_1P_2P_2$ is the pole face, the magnetic lines being at right angles to this plane. In this case the cathode ray, a charge e moving with velocity v, behaves like a current element ev in a magnetic field of strength H. The path of the ray is a circle of radius of curvature ρ. The force acting on the ray is Hev, and we have therefore

$$mv^2/\rho = Hev$$

or

$$H\rho = mv/e$$

In Fig. 1,

$$2\rho y_1 = \lambda^2 \text{ (approximately for a circular path)}$$

i.e.

$$y_1 = \frac{eH}{2mv}\lambda^2$$

or at any point on the path of the ray

$$y = \frac{eH}{2mv}x^2 \quad \text{and} \quad \frac{dy}{dx} = \frac{eH}{mv}x$$

At the point A′, where $x = \lambda$ and $y = y_1$, when the rays leave the magnetic field

$$y_1 = \frac{eH}{2mv}\lambda^2 \quad \text{and} \quad \tan\alpha = \frac{dy}{dx} = \frac{eH}{mv}\lambda \text{ (when } x = \lambda)$$

Hence

$$h = l\tan\alpha + y_1$$
$$= \frac{eH\lambda l}{mv} + \frac{eH}{2mv}\lambda_1^2$$

i.e.

$$h = H\frac{e}{mv}\lambda(l + \tfrac{1}{2}\lambda) \quad . \quad . \quad . \quad . \quad (3)$$

which is another fundamental relation for oscillograph design.

(*d*) *Penetrating power*.—Lenard (*Wied Annalen*, 1895) showed that for fast-moving cathode rays the extent of absorption in different substances is roughly proportional to the density. The penetrating power of the cathode ray varies very greatly with its speed. The highest-speed rays (10^{10} cm per sec.) can only penetrate 2 or 3 mm of air at normal temperature and pressure.

It has been shown theoretically by Sir J. J. Thomson, and confirmed experimentally by Whiddington * and others,† that the loss of velocity of cathode rays in passing through matter is expressed by the relation

$$v_i^4 - v_e^4 = ad \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where v_i is the velocity with which the rays impinge on the absorbing layer, and v_e is the velocity of emergence after passing through a thickness d; a is a constant depending on the density of the absorber (e.g. Whiddington gives a as equal to 2×10^{40} for air, 732×10^{40} for aluminium, $2\,540 \times 10^{40}$ for gold, whilst Terrill states that $a = 5 \cdot 05 \times 10^{42}\rho$, where ρ is the density of the material).

The above relation (4) gives us a simple expression for the maximum depth of penetration of rays of velocity v into a layer of solid matter. In this case $v_e = 0$ and $d = t$, the maximum thickness of matter penetrated.

Thus

$$t = v^4/a \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

the maximum thickness t varying directly as the fourth power of the velocity of the cathode rays and approximately inversely as the density of the absorbing layer.

In Equation (1) above, it is shown that the velocity of the cathode rays is proportional to the square root of the accelerating voltage V; hence we may write Equation (5) in the form

$$t = kV^2/a \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

i.e. the thickness of layer penetrated is proportional to the square of the voltage generating the cathode rays.

III. Voltage, Current and Photographic Sensitivity of Cathode-Ray Oscillographs.

By making use of the fundamental relations (1) to (6) obtained in Section II, we are enabled to design a cathode-ray oscillograph to fulfil any desired conditions of voltage, current or photographic sensitivity.

(*a*) *Voltage sensitivity*.—It will be seen, from consideration of Equation (2) above, that the final deflection h of a beam of cathode rays after passing through an electrostatic field of strength E/d and length λ is directly proportional to the potential difference E applied to the deflecting plates, inversely proportional to v^2, and directly proportional to a constant involving the dimensions of the deflecting plates. The value of h given by Equation (2) may be considerably simplified if we introduce the actual values of some of the constants involved. Thus we may substitute for v the value given in Equation (1), viz. $V = 5 \cdot 95\sqrt{(V)} \times 10^7$ cm per sec., and for e/m the constant $1 \cdot 772 \times 10^7$ electromagnetic units or $5 \cdot 316 \times 10^{17}$ electrostatic units. In this manner the expression for h reduces to

$$h = 0 \cdot 50\ EK/V \text{ cm}$$

where E the potential difference across the deflecting plates, and V the potential difference generating the cathode rays, are both expressed in volts; and $K = (\lambda/d)\,(l + \tfrac{1}{2}\lambda)$, the voltage constant of the oscillograph, depends on the dimensions of the oscillograph.

The voltage sensitivity of the oscillograph is therefore given by

$$\frac{K}{2V} \text{ cm per volt} \quad \text{or} \quad \frac{2V}{K} \text{ volts per cm} \quad . \quad (7)$$

This expression holds good for any design of cathode-ray oscillograph using parallel deflecting plates. It will be seen that the sensitivity (expressed in cm per volt) can be increased by (*a*) decreasing V, the voltage generating the rays, or (*b*) increasing K, the oscillograph "voltage constant."

K can be increased by increasing l and λ (the length of the plates) or by decreasing d (the distance apart of the plates). There are, of course, practical limits to the oscillograph constant.

For example, in one of the oscillographs used by the author, $\lambda = 8$ cm, $d = 1$ cm, and $l = 16$ cm

* R. Whiddington: *Proceedings of the Royal Society*, A, 1911–12, vol. 86, p. 370.

† B. F. J. Schonland: *ibid.*, A, 1923, vol. 104, p. 235; and H. M. Terrill: *Physical Review*, 1923, vol. 22, p. 101.

approximately; i.e. $K = 160$ whence $h = 80/V$ cm per volt, or the sensitivity expressed in volts per cm deflection is equal to $V/80$. For a voltage $V = 3\,000$ generating the cathode rays the sensitivity is 37·5 volts per cm, which is in good agreement with that actually observed. With an accelerating voltage of only 300 volts the sensitivity would be increased ten-fold, i.e. to 3·75 volts per cm. It is evident from (7) above that by suitably choosing (*a*) the voltage V producing the cathode rays, and (*b*) the dimensions of the deflecting plates and the distance from the screen, a very wide range of voltage sensitivity can be obtained. Under certain circumstances, to which we shall refer later, the minimum value of V is limited, in which case increased sensitiveness can be obtained only by method (*b*).

(*b*) *Current sensitivity*.—The effect of a current on the cathode stream is of course dependent on the magnetic field which it produces. The extent of deflection of the cathode rays by a magnetic field is indicated by Equation (3) above, where it is shown that the deflection obtained is directly proportional to the strength of the magnetic field (and hence to the current exciting the magnet) and inversely proportional to the velocity of the cathode rays. The deflection is also proportional to a constant involving the dimensions and distance apart of the magnet poles, and to their distance from the photographic plate or phosphorescent screen.

By substituting the values $e/m = 1\cdot772 \times 10^7$ electromagnetic units and $v = 5\cdot95\sqrt{(V)} \times 10^7$ cm per sec. in Equation (3) we find

$$h = 0\cdot298\frac{H}{\sqrt{V}}\lambda(l + \tfrac{1}{2}\lambda)$$

This expression implies that the magnetic sensitivity of the oscillograph is

$$\left.\begin{array}{ll} & \dfrac{3\cdot36\sqrt{V}}{\lambda(l + \frac{1}{2}\lambda)} \text{ gauss per cm deflection} \\ \text{or} & \dfrac{0\cdot298\lambda(l + \frac{1}{2}\lambda)}{\sqrt{V}} \text{ cm deflection per gauss field strength} \end{array}\right\} \quad (8)$$

It is more convenient, however, to express sensitivity in terms of current strength or ampere-turns. Consider a magnet of N turns wound on a laminated iron core with a large air-gap * of length d, the length of the pole-face being λ in the direction of the cathode stream. The strength of the magnetic field in the air-gap is given by

$$H = \frac{4\pi NI}{10d}, \text{ where } I \text{ is the current in amperes.}$$

Hence we may write for the deflection of the cathode rays

$$h = 0\cdot298\frac{4\pi NI\lambda}{10d\sqrt{V}}(l + \tfrac{1}{2}\lambda)$$

or

$$h = \frac{0\cdot375K'}{\sqrt{V}}NI$$

where K' is the "current constant" * of the oscillograph and is equal to $(\lambda/d)(l + \frac{1}{2}\lambda)$. The current sensitivity of the oscillograph is therefore given by

$$\left.\begin{array}{ll} & 0\cdot375K'/\sqrt{V} \text{ cm per ampere-turn} \\ \text{or} & 2\cdot67\sqrt{(V)}/K' \text{ ampere-turns per cm deflection} \end{array}\right\} \quad (9)$$

The values of magnetic sensitivity (8) apply to all cathode-ray oscillographs, whether the magnetic fields are produced by iron-cored magnets with large air-gaps or by solenoidal coils with air cores.

The current sensitivity (measured in cm per ampere-turn) is increased by:—

(*a*) Decreasing the voltage V generating the rays.
(*b*) Increasing K' the "current constant" of the oscillograph. K' can be increased by increasing the length λ of the magnet or by decreasing the gap d, or by increasing the distance l from the magnet to the screen or photographic plate.

For example, in an oscillograph now in use, $\lambda = 1\cdot8$ cm, $d = 1\cdot8$ cm, $l = 16$ cm approximately, whence $K' = 16\cdot9$. Consequently $h = 6\cdot35/\sqrt{V}$ cm per ampere-turn. With a magnet of 700 turns a current of 0·03 ampere produces a deflection of 2·5 cm approximately when the voltage V accelerating the cathode rays is 3 000. The calculated value of h is $\frac{6\cdot35}{\sqrt{3\,000}} \times 700 \times 0\cdot03$ cm, i.e. 2·44 cm, which is in good agreement with the observation.

It will be noticed that the current sensitivity of the oscillograph is inversely proportional to $\sqrt{V}$, i.e. to v, or to the momentum of the rays; whereas the voltage sensitivity was shown to vary inversely as V, i.e. as v^2, or as the kinetic energy of the rays.

(*c*) *Photographic sensitivity*.—It is well known that cathode rays when they fall on a screen of phosphorescent material, e.g. willemite or calcium tungstate, produce visible luminous effects. In a similar manner when these rays strike the emulsion of a sensitive photographic plate a blackening effect (after development) is produced. These phosphorescent and photographic effects depend, as one would anticipate, on the velocity of the cathode rays. The higher the velocity of the rays the greater is the energy available and the greater is their power of penetration into the phosphorescent material or the photographic film. It was shown in Section II(*d*) that the maximum depth of penetration t of a cathode ray into a layer of matter is proportional to the fourth power of its velocity v (i.e. to the square of the exciting voltage V) and approximately inversely as the density of the absorbing layer. Thus $t = v^4/a$ cm, where a is a constant depending on the absorbing material.

The ordinary photographic film consists of an emulsion of silver bromide in gelatine. When cathode rays fall on such a layer their energy is rapidly absorbed by numerous collisions with the molecules of gelatine and silver bromide. The value of the constant a in

* The reluctance of the air-gap is here considered to be very large compared with that of the iron circuit. The same line of argument applies also to any air-core solenoid used to deflect the cathode rays.

* It should be observed that the oscillograph constants K and K' refer to voltage and current deflections respectively; they are entirely independent constants.

this case is estimated to be 10^{43} for an ordinary gelatine emulsion plate ($\Delta = 2\cdot0$) whence

$$t = v^4 \times 10^{-43} \text{ cm approximately.}$$

Combining this with Equation (1), which gives the velocity v in terms of generating voltage V,

$$t = 1\cdot25 V^2 \times 10^{-12} \text{ cm approximately,}$$

giving the thickness t in cm which cathode rays of any voltage V can penetrate into a photographic film.

Now the thickness of the film on an ordinary photographic plate is approximately 10^{-3} cm; hence we can calculate the percentage depth of penetration of rays of different velocities into this film.

V, in volts	t, in cm	Percentage thickness of film penetrated
30 000	$1\cdot1 \times 10^{-3}$	100 (complete penetration)
3 000	$1\cdot1 \times 10^{-5}$	1
300	$1\cdot1 \times 10^{-7}$	0·01

It will be seen from the table that high-velocity cathode rays (30 000 volts) can penetrate completely an ordinary photographic layer, and may therefore be expected to have a very efficient photographic action. Lower-velocity (e.g. 3 000 volts) rays, however, can only penetrate a very small depth, 1 per cent of the film, the photographic effect in this case being superficial only, since the rays never reach the lower layers of sensitive silver-bromide granules. As the velocity is still further diminished, e.g. with 300-volt rays, the depth of penetration is practically zero and the photographic effect is negligible in comparison with that of the higher-velocity rays.

In a previous paper by the author * methods of increasing photographic sensitivity were described. The first of these methods consists in increasing the proportion of silver bromide to gelatine in the emulsion. Thus in the emulsion of an ordinary gelatine plate the relative proportion of silver bromide to gelatine is approximately 0·88 by weight and 0·174 by volume, whereas in a special form of Schumann plate made by Hilgers the proportion is 90 by weight and 18·2 by volume.† That is, for equal volumes of the film in Schumann and ordinary gelatine plates, the former contains 100 times as much silver bromide as the latter. The density of the film is thereby increased 3 times, but the chance of collision between cathode particles and AgBr molecules is increased 100 times. On these grounds, therefore, it would seem probable that the photographic effect produced by low-velocity cathode rays (i.e. rays which do not completely penetrate the film) is about 33 times greater in the Schumann plate than in an ordinary plate. Using these plates, good photographic effects have been obtained with rays of a velocity as low as that corresponding to 1 000 volts; below this velocity, however, the photographic effects are relatively feeble.

* *Proceedings of the Physical Society of London*, 1923, vol. 35, p. 109.
† I am indebted to Mr. A. G. Milligan, B.Sc., for the careful determination of these quantities.

The second method of increasing photographic sensitivity employs an admixture of phosphorescent material (e.g. calcium tungstate) with the photographic emulsion, or the use of a thin layer deposited on the emulsion.* The photographic effect is now due to two causes: (1) The direct effect of the cathode rays, and (2) the indirect luminous effect of the phosphorescent material in close contact with the sensitive granules.

The two methods just mentioned of increasing photographic sensitivity have proved very successful in practice and have considerably extended the possibilities of the low-voltage type of cathode oscillograph. In spite of such improvements, however, it must be realized that with diminishing velocity of cathode rays the photographic difficulties rapidly increase.

IV. Recent Commercial Forms of Cathode-Ray Oscillograph.

At the present time there are three distinct types of cathode-ray oscillograph which may be regarded as having reached the commercial stage, i.e. the stage at which they are conveniently reproducible and are likely to prove serviceable instruments in physical and electrical engineering laboratories. The first of these oscillographs is the high-voltage type designed by Monsieur A. Dufour † and operating at 60 000 volts or thereabouts. The second type is one originally proposed by Sir J. J. Thomson and developed to its present commercial form by the author.‡ This oscillograph operates on a voltage of the order of 3 000 volts. The third type, due to the Western Electric Co.,§ operates on 300 volts, but unlike the other oscillographs just mentioned can only be used for visual observations, no provision being made for photography.||

All these oscillographs employ the fundamental principles of the Braun tube, comprising essentially an evacuated vessel with means for producing a narrow pencil of cathode rays, electrostatic deflecting plates, magnetic field, and phosphorescent screen. In the Dufour oscillograph and that designed by the author, provision is made for a number of photographic plates in the vacuum chamber, and special circuits (electromagnetic and electrostatic) are employed to traverse the spot at known speeds across the plate.

(*a*) *High-voltage oscillograph.*—This instrument has been brought to a high degree of efficiency by Monsieur A. Dufour. A diagrammatic view ¶ of his oscillograph is shown in Fig. 2. As in the original form of Braun tube, the cathode rays are produced in a soft vacuum, a voltage of 60 000 being employed to accelerate the negative electrons initially in the tube and to produce others by collision. The cathode is a concave disc of aluminium "e." The beam of cathode rays is reduced to a fine

* In the latter case the phosphorescent material is washed off on development of the plate.
† A. Dufour: *L'Onde Electrique*, 922, vol. 1, pp. 638 and 699, and 1923, vol. 2, p. 19.
‡ A. B. Wood: *Proceedings of the Physical Society of London*, 1923, vol. 35, p. 109.
§ J. B. Johnson: *Optical Society of America*, 1922, vol. 6, p. 701.
|| Reference is made here to the recording of a wave-form or impulsive effect in a single traverse of the plate.
¶ Taken from Dufour's paper, *loc. cit.*

pencil of rays by means of a diaphragm "f" which, connected to the metal body of the oscillograph, forms the anode. Outside the tube, near "v," suitable electrostatic deflecting plates and electromagnets are arranged in accordance with experimental requirements. After passing through these electrostatic and magnetic fields the cathode rays enter the camera chamber "a" where they strike the cylindrical photographic film "g" or the glass plates "h." When a film is used the cylindrical drum supporting it can be rotated by means of an external magnetic device "p" controlling the spindle "n" through the glass cap "o."

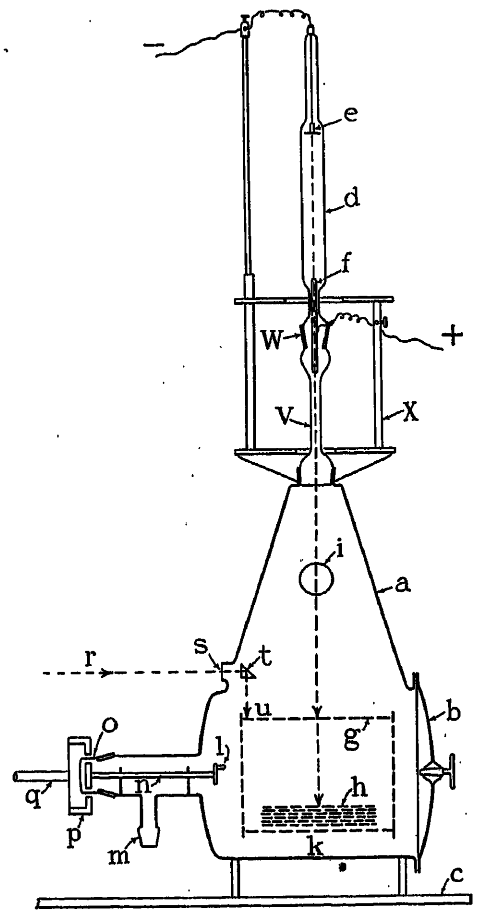


FIG. 2.

In this case a time scale can be optically recorded on the edge of the film by way of the window "s" and totally reflecting prism "t." The side "b" of the camera chamber is removable. A vessel "k" containing P_2O_5 is fitted inside the camera to absorb water vapour, which is emitted in the vacuum from the gelatine emulsion of the film or plate. The rotating drum and film are only used in low-frequency work. At very high frequencies the drum is removed and a pile of photographic plates "h" substituted. The cathode rays are in this case deflected at a known speed across the plate by means of an electromagnet in which the current is increasing at a known rate. The speeds of deflection possible by such methods are far greater than any mechanical speeds conceivable with the rotating drum.

With this oscillograph Dufour has obtained beautiful records of high-frequency alternating-current effects and impulsive or "transient" phenomena. He has employed the oscillograph most successfully in recording wave-forms of high-frequency wireless oscillations up to a frequency of 200 million periods per second, i.e. corresponding to a wave-length of 1·5 metres. The actual velocity of the cathode-ray spot in making such a record is approximately 4×10^8 cm per second. It will be realized from this fact that the photographic effect of the high-voltage cathode ray is very intense.

As we have seen in Section III (*c*), the photographic sensitivity of a 60 000-volt oscillograph is very great, for the rays attain a sufficiently high velocity to penetrate any ordinary photographic film. On the other hand, the electrostatic and current sensitivities of this type of oscillograph are correspondingly low. Dufour does not refer in his paper to the dimensions of the electrostatic deflecting plates or the magnet coils, but he states that the voltage sensitivity of his oscillograph is 100 volts per cm, whilst the current sensitivity is 10 ampere-turns per cm. Using Equations (7) and (9) given above for the voltage and current sensitivity respectively, we find that the voltage and current constants of his oscillograph are $K = 1\,200$ and $K' = 68$ respectively. These values are of course dependent on λ, d and l for the electrostatic plates and magnetic circuit. In making comparisons of the sensitivity, the values of the constants K and K' should be taken as the same in both cases. This point will be referred to later under (*d*).

It has already been pointed out that the Dufour oscillograph employs a soft vacuum, i.e. the apparatus contains sufficient residual gas to permit of production of ions by collision. Now the pencil of cathode rays as it passes between the deflecting plates ionizes this residual gas to some extent, and the space between the deflecting plates becomes conducting. If the plates themselves were included inside the vacuum chamber this leakage from one plate to the other would preclude, or at any rate impair, the use of the oscillograph for the accurate recording of certain types of electrostatic voltage effects. Dufour attempts to avoid this difficulty by fitting the deflecting plates outside the vacuum tube. The insulation between the plates is in this case practically perfect, but the space charge in the deflecting chamber is still an objectionable feature.

(*b*) *Medium-voltage oscillograph.*—An oscillograph of this type was first proposed by Sir J. J. Thomson.* Since that time the original apparatus has been considerably modified in design, particularly with a view to improving its mechanical construction and robustness and to the production of a form of instrument † which should be of general service in a laboratory. Considerable improvements have also been made in the photographic arrangements.

Strictly speaking, it would be more correct to refer to this form of oscillograph as the low-voltage type, for it has been designed to operate on a minimum

* J. J. THOMSON: *Engineering*, 1919, vol. 107, p. 543; and D. A. KEYS *Philosophical Magazine*, 1921, vol. 42, p. 473.

† A. B. WOOD, *loc. cit.*

voltage consistent with good photographic results at high speeds. It has been shown in Section III (c) that the photographic effect produced by cathode rays falls off rapidly as the voltage of the rays is decreased, and it becomes more and more difficult to obtain good photographic sensitivity as the voltage is reduced. It has been found experimentally by the author that cathode rays of voltage less than 1 000 are very weak photographically, and until improved methods of focusing these low-voltage rays, or of increasing their penetrating power,* have been devised it is not probable that an oscillograph can be designed to operate on voltages much lower than this. The normal voltage of operation of the oscillograph is 3 000 volts, the cathode rays in this case giving excellent photographic records at high speeds under suitable photographic conditions. A diagrammatic section of one form of this oscillograph is shown in Fig. 3.* A more recent form, mounted in cabinet, is shown in Fig. 4. It will be seen that the oscillograph is of very robust construction, consisting almost entirely of metal parts fitted together in such a manner that any part can easily be removed and replaced, or modified to suit the particular circumstances under which it is required. The more important parts of the instrument are fitted together and rendered airtight by means of greased conical joints. Thus it will be seen from Fig. 3 that the filament holder, the bulb, the deflecting tube, the various pumping connections and plugs operating the camera can be taken apart and refitted in a few seconds. This feature of the oscillograph is a great convenience in the laboratory. The base of the oscillograph is a heavy brass casting containing the camera and supporting the brass cylindrical deflecting tube which, in turn, supports the bulb and filament holder. The latter is constructed so that the position of the filament in the bulb, i.e. its distance from the anode, is adjustable. A burnt-out or defective filament can be replaced immediately by unscrewing it from the filament holder and fitting a new one—the same operation as fitting a new bulb to a flash-lamp. The filament itself is a flat spiral of tungsten or lime-coated platinum wire heated by a local insulated 4-volt battery and connected to the negative of the 3 000-volt supply. As in the Coolidge X-ray tube the spiral is surrounded by a metal sheath which exerts a focusing

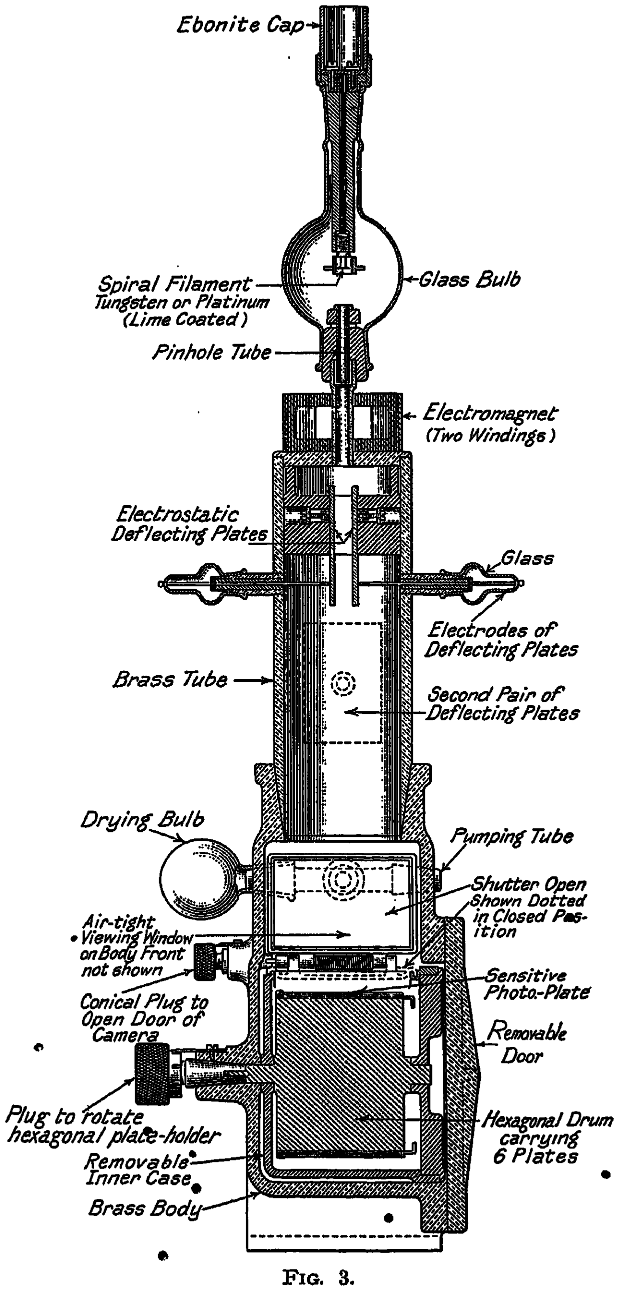


Fig. 3.

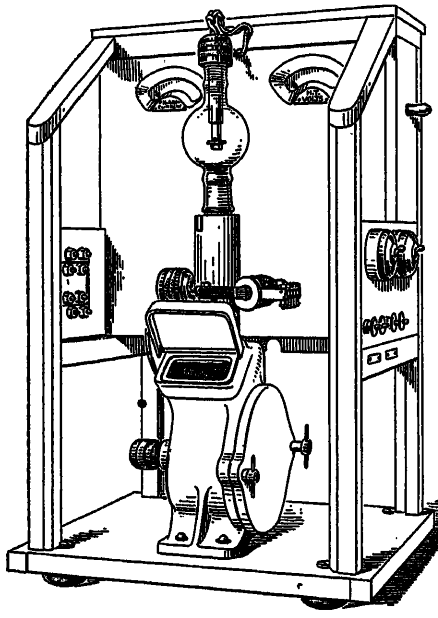


Fig. 4.

* For example, by application of high accelerating voltages *after* deflection by electrostatic and magnetic fields.

* These oscillographs are now manufactured by Messrs. H. Tinsley & Co., South Norwood.

action on the cathode beam. The latter travels towards the pinhole tube—two thin metal diaphragms about 3 in. apart and pierced by small holes about 5 or 10 mils diameter—this forming part of the anode with the metal body of the oscillograph, which is earthed.

After leaving the pinhole tube the narrow pencil of cathode rays enters the deflecting tube where it passes between two pairs of electrostatic deflecting plates, mutually at right angles, and the poles of an electromagnet. The latter may or may not contain iron in the circuit, according to the purposes for which it is required. The deflecting plates are suitably insulated and fixed in position and are connected to terminals outside the oscillograph through air-tight fittings (glass cones in Fig. 3).

After leaving the deflecting tube the rays enter the camera chamber, where they ultimately strike the door of the camera. This door is coated on its upper surface with phosphorescent material—calcium tungstate or willemite—which can be viewed through a window fitted in front of the body of the oscillograph. When a photographic record is required the door of the camera, and hence the observing screen, are removed by turning a conical plug on the side of the instrument. This exposes one of six plates fitted on a hexagonal block, which can be turned from outside as desired by means of another conical plug (see Fig. 3). By means of a hinged cover plate, light is prevented from entering through the viewing window when an exposure is being made. The hexagon with its six plates is mounted inside a light-tight casing, which can be removed from the oscillograph in broad daylight, the plates being subsequently dealt with in a dark-room.

The vacuum can be obtained by means of any of the standard high-vacuum pumps at present on the market. With an ordinary Gaede mercury pump, and a backing pump (reducing to about 1 mm pressure) the desired vacuum can be obtained in about 15 minutes, starting at atmospheric pressure. It is of course essential, unless vapour pumps are used, that suitable drying material (e.g. P_2O_5) be used to absorb water vapour. When using the oscillograph it is customary to maintain the pump connection, but this is not always necessary when a good vacuum has been reached and the filament is free from gas.

It was pointed out in Section III (*c*) that low-voltage cathode rays can only penetrate thin films of matter (of the order 10^5 cm) and that special photographic plates, Schumann plates * having a large proportion of silver granules and a minimum of gelatine, give much better results than ordinary gelatine-coated plates with a smaller proportion of silver. For high-speed records with 3 000-volt rays Schumann plates have proved far superior to ordinary plates. For comparatively low-frequency records (1 000 to 10 000 periods per sec.), however, Paget half-tone plates † have given moderately good results. The lower the voltage employed to generate the cathode rays the more necessary it becomes to employ Schumann plates.

As in the Dufour oscillograph, the cathode-ray stream is traversed across the photographic plate by electrostatic or electromagnetic methods, the rate of traverse depending entirely on the time constant of the condenser or inductance circuit respectively. These methods, giving an approximately linear time scale, have proved satisfactory up to the very highest speeds —far in excess of what is possible by ordinary mechanical methods of driving a moving film. At lower speeds other methods, as, for example, the rotating potentiometer method,* etc., may be employed. By such means the time for the cathode spot to cross the plate may easily be varied from 1 sec. to 10^{-6} sec.

In making a photographic record of an alternating-current wave-form, e.g. at 10 000 periods per sec., the rate of traverse of the spot is previously adjusted by observation of the phosphorescent screen. The procedure is briefly as follows (see Fig. 5). A steady current is passed through winding A of the electromagnet and adjusted until the spot is deflected from position (1) to position (2) off the left-hand edge of the screen.† The alternating voltage, of which the waveform is required, is then applied to one pair of electrostatic deflecting plates, thus causing the spot to oscillate along a line (3) at right angles to the direction of magnetic deflection. On closing the circuit through winding B of the magnet, which is more powerful than,

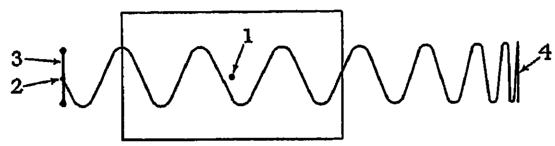


FIG. 5.

and in opposition to, winding A, the spot crosses the plate from its first position (3) on the left to another position (4) well away on the right, and, in doing so, leaves a trace of the wave-form to be recorded. The speed of traverse can be varied by varying the voltage, inductance and resistance in the circuit of B winding.

These operations, illustrated diagrammatically in Fig. 5, are first carried out visually on the phosphorescent screen, the final record being made on the photographic plate. For very high speeds of traverse it is advantageous to use the two pairs of electrostatic deflecting plates, following a procedure on similar lines to that just outlined. In this case, of course, the traverse of the spot is produced by the voltage-rise across a condenser in series with a resistance. The initial deflection of the spot to the left may, as before, be obtained by means of the electromagnet or, alternatively, by means of a steady voltage applied to the deflecting plates.

By these methods good records have been obtained of very high-speed alternating and impulsive or transient electrical effects. Reference will be made to the applications of the oscillograph in a later section of the paper.

Since this type of oscillograph employs a hot cathode of tungsten or lime-coated platinum, the vacuum is

* Supplied by Hilgers, Ltd., Camden Town.
† These plates were recommended to me by Sir J. J. Thomson.

* A. B. WOOD: *Proceedings of the Physical Society of London, loc. cit.*
† The spot can still be observed under these conditions by coating the body of the camera at this place with phosphorescent material.

hard and there is no tendency for the cathode stream, as it passes between the deflecting plates, to produce ionization and thereby render the space between the deflecting plates conducting. It is this feature which makes the oscillograph especially suitable for recording electrostatic changes where only small quantities of charge are involved. Slight leakage between the plates would, under such circumstances, prove fatal to the accurate recording of voltage changes.

(c) *Low-voltage oscillograph.*—A description of this instrument is given in the *Physical Review* for August 1923 by J. B. Johnson, and the tube is manufactured and supplied by the Western Electric Co. As has already been stated, the tube is only suitable for visual observations, and cannot therefore be described as an oscillograph in the same sense that the description applies to the Duddell and Einthoven instruments and to the types (a) and (b) of cathode-ray oscillographs described above. In these instruments a permanent photographic record of a wave-form or of any electrical disturbance can be obtained by a single traverse of the spot (light or cathode rays) across the photographic plate. With the Western Electric instrument, however, no provision is made for photography other than that provided in the original form of Braun tube. The Western Electric tube, however, operates on a low accelerating voltage, resulting in increased sensitivity and in diminished cost of accessory apparatus. The high-voltage generator and vacuum pumps are not required, for the tube operates on 300 volts and is evacuated at the works and sealed off permanently. The design is extremely simple, the filament (thoriated tungsten), pinhole tube anode, and two pairs of deflecting plates all being carried on a simple mounting at one end of the tube, a phosphorescent screen forming the other end. By means of a special construction of filament shield and by controlling the filament current the beam of cathode rays is focused on the screen. This focusing action is ascribed by H. J. van der Bijl and J. B. Johnson to the difference in mobility of the positive and negative electrons in the residual gas in the tube. Some of the cathode rays in passing through the residual gas produce ionization. Both the colliding electrons (the cathode rays) and the secondary electrons leave the beam, but the heavy positive electrons drift out of the beam much more slowly. Consequently the positive electrons accumulate in the path of the cathode rays and tend to pull the negative electrons (the cathode rays) inwards, with the result that they are brought to a focus. When the filament current is increased, the total positive ionization of the beam increases, the field around the beam becomes stronger, and the electrons are brought to a focus at a shorter distance. The focusing of the beam on the phosphorescent screen is therefore brought about by control of the filament current. The life of the filament is stated by the makers to be 200 hours. When a filament is burnt out it is necessary to obtain a complete new tube.

The Western Electric cathode-ray tube is mainly suitable for the examination of alternating-current phenomena reproduced on the screen in the form of Lissajous figures. The tube has been used, however, for the visual examination of transient electrical effects,* but it is not particularly suitable for this purpose, especially if the effects are of very short duration.

On account of the presence of gas in the tube, the oscillograph is quite unsuited for the examination of transient electrostatic effects where a small electrostatic charge varying with time is to be indicated by a deflection of the cathode beam. The makers claim that the tube may be used in the examination of explosion pressures by the aid of a piezo-electric crystal,† but this is not the case. For such a purpose it is essential that the leakage current between the electrostatic deflecting plates be negligible [as is the case with types (a) and (b) oscillographs described above]. The ionization between the deflecting plates of the Western Electric tube is, however, considerable and leakage currents are serious, thus rendering the tube unsuited for examination of transient electrostatic effects. In cases where the power available is unlimited this difficulty of course does not arise.

The electrostatic and current sensitivity of the low-voltage tube are of course very great, but, as we have already seen, the photographic sensitivity is correspondingly small.

Photographs of Lissajous figures or other repetition phenomena can be obtained indirectly by means of an auxiliary camera focused on the phosphorescent screen. Transient or impulsive electrical effects of an irregular or non-periodic character cannot be photographed with the oscillograph in its present form.

(d) *Comparison of the three types.*—It is proposed in this Section briefly to summarize the principal features of the three types of cathode-ray oscillograph described above. For the purpose of comparison we shall consider type (a) to be operated at 30 000 volts, type (b) at 3 000 volts, and type (c) at 300 volts, although it will be clear that in all the types the voltage may be varied in practice over a considerable range.

(i) *Electrostatic sensitivity.*—This we have seen in Section III (a) to be inversely proportional to the operating voltage V. Hence if we take the sensitivity to be unity in the 30 000-volt instrument, it will be 10 and 100 in the 3 000- and 300-volt tubes respectively, other conditions (i.e. dimensions of tube and deflecting plates) remaining the same in the three cases.

(ii) *Magnetic or current sensitivity.*—In this case [see also Section III (b)] we find the sensitivity to be inversely proportional to $\sqrt{V}$, i.e. the 30 000-, 3 000- and 300-volt types have the relative sensitivities 1, 3·16 and 10 respectively.

(iii) *Photographic sensitivity.*—It has been shown [see Section III (c)] that the depth of penetration of the cathode rays is proportional to the square of the operating voltage. Apart from other considerations, therefore, it seems reasonable to suppose that the photographic action will be determined by V^2. Hence the relative photographic sensitivities might be expected to be roughly proportional to 1, 10^{-2} and 10^{-4} respectively for cathode rays of voltages 30 000, 3 000 and 300. Unless auxiliary means are provided ‡ for

* R. A. Watson Watt: *Wireless World and Radio Review*, 1923, vol. 12, p. 600.
† D. A. Keys *loc. cit.*
‡ For example as indicated in the footnote on page 1052.

increasing the photographic action of low-velocity rays, it seems improbable, therefore, that a cathode-ray oscillograph of voltage much lower than 1 000 will be forthcoming.

(iv) *General.*—From the point of view of cheapness, convenience, and simplicity of operation, the Western Electric 300-volt tube is of course in the forefront. It is a very useful instrument for laboratory testing purposes where rough visual observations are all that is required. An oscillograph, to be of real value to the engineer and physicist, must, however, be capable of giving permanent photographic records of high-frequency effects, in a manner similar to that in which the Duddell and Einthoven instruments are used to record low-frequency phenomena. It is in this important feature that the 30 000-volt and 3 000-volt oscillographs are so valuable. These oscillographs can record wireless frequencies (of the order 10^6 periods per sec.) in a single traverse across the photographic plate. Sensitivity can be increased by means suggested earlier in the paper, and it is confidently anticipated that in this particular they can easily be brought to the require-

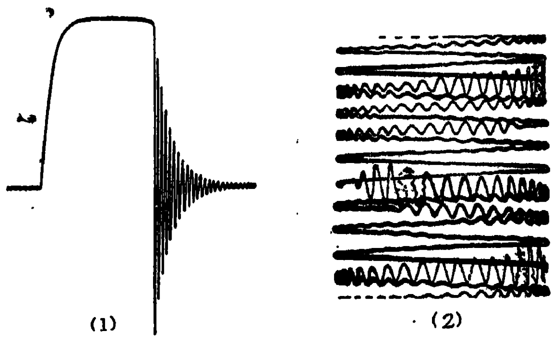


FIG. 6 (*a*).—60 000-volt oscillograph (Dufour).

(1) Make and break of direct current in inductive circuit. Condenser across break.
(2) Damped oscillations 150 × 10^6 frequency (wave-length = 2 metres).

ment of general practice. When compared with Duddell and Einthoven oscillographs, the cathode-ray type is obviously lacking in one important feature, viz. that of a multiple recording system, by means of which voltage and current characteristics may be recorded simultaneously. The future will doubtless provide means of generating two or possibly more cathode-ray streams falling on the same plate and actuated by voltage and current independently. In the meantime, however, we must make the most of the very valuable instruments at present available for recording frequencies and impulsive electrical effects which were a short time ago quite outside the range of laboratory oscillographs.

V. APPLICATIONS.

The applications of cathode-ray oscillographs are almost infinite in number and variety. On account of their fundamental property of recording faithfully any electrical effect whatsoever without distortion, they can be employed over a range of frequency from zero to as high as is conceivable in an electrical circuit. Dufour has used his high-voltage oscillograph to record frequencies varying from zero to 10^8 periods per second.

The 3 000-volt oscillograph (using Schumann plates)

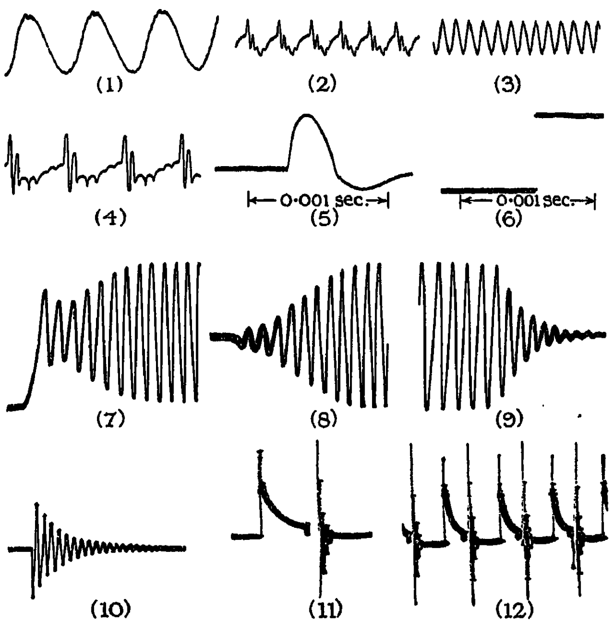


FIG. 6 (*b*).—3 000-volt oscillograph (Admiralty Research Laboratory).

(1, 2, 3 and 4) A.C. wave-forms from valve oscillator at frequencies of 1 000 2 000, 10 000 and 5 000 respectively.
(5) Back E.M.F. at break of circuit containing a large inductance—time scale, 3 cm = 0·001 sec.
(6) "Make" of 40 volts. Speed 3 cm = 0·001 sec. Illustrating instantaneous and dead-beat action of oscillograph.
(7, 8, 9) Growth and decay of oscillations in a valve circuit, frequency 10 000 per sec.
(10) Oscillations in discharge of a condenser through an inductive circuit.
(11 and 12) Secondary voltage fluctuations in spark coil, showing make and break effects.

can be used over the same range. It has been used to record high-speed impulsive effects, growth and decay of oscillations in valve circuits, characteristics of valves, impulsive effects in oscillatory circuits containing inductance capacity and resistance, dielectric losses, and for other purposes too numerous to mention.

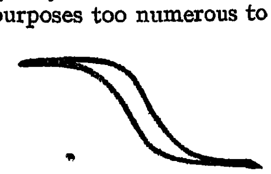


FIG. 6 (*c*).—300-volt oscillograph (Western Electric Co.).

Lissajous figure with alternating current (long exposure using ordinary camera focused on phosphorescent screen).

In Fig. 6 are reproduced a few typical cathode-ray oscillograms obtained by the three types of oscillographs described above.

In conclusion the author desires to express his indebtedness to the Admiralty for permission to publish this paper.

MEASUREMENTS IN ELECTRICAL ENGINEERING BY MEANS OF CATHODE RAYS.*

By Professor J. T. MACGREGOR-MORRIS, Member, and R. MINES, B.Sc., Student.

(*Paper first received 22nd September, 1924, and in final form 23rd May, 1925.*)

SUMMARY.

This paper is intended as a survey of the present state of knowledge on the subject of the use of cathode rays for measurement purposes in electrical engineering, and specially with a view to possible future developments.

Part 1 introduces the subject of measurement methods. Section (I) describes various ways in which information on physical quantities may be obtained by applying them to suitably devised instruments, and in Section (II) is given the history of the development of such instruments, with special reference to those for studying variable quantities. In Section (III) are described various means of producing cathode rays and how they came to be applied to measuring instruments.

Part 2 deals in greater detail with measuring apparatus using cathode rays (i.e. an "electron jet") as a "pointer." Sections (IV) and (V) describe historically the development of such apparatus by successive workers in the field, with brief references to the purposes for which it was devised. Certain special problems arise in the use of such apparatus for accurate measurement, and Sections (VI) and (VII) indicate how the solution of these problems has been tackled. In Section (VIII) the auxiliary apparatus found necessary for the study of variable quantities is described.

Part 3 contains a brief résumé of some of the limitations of the methods described in the paper, and indicates some possible lines of future development.

In an Appendix is given an investigation (partly mathematical and partly historical) of certain essential properties of the electron jet as used in the instruments described.

TABLE OF CONTENTS.

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate

PART 1.

INTRODUCTORY.

For a period of more than half a century it has been known that cathode rays are deflected by a magnetic field and also by an electrostatic field; but it was the classic work of J. J. Thomson on the electron, published in 1897, which showed how reasonable precision could be obtained in such measurements.

This notable work in the realm of pure physics paved the way for the application of cathode rays to electrical engineering measurements, and since Braun made the first practical use of these rays, and H. J. Ryan added notably to the subject, there have been an ever-increasing number of investigators working at the development of the cathode-ray tube and its applications. Further, the extraordinarily rapid development of wireless or high-frequency engineering has recently given an even greater impetus to this study.

During periods of rapid progress such as this it is well at times to stand back and make the attempt to survey the entire field, so that one may see more clearly the directions in which new ground may profitably be broken, and also determine as far as possible the limitations.

It is with this object that the preparation of this paper has been undertaken, in the hope that it may prove of real service to many interested in this subject.

Part of the material and some of the work recorded were collected in connection with a research carried out by the authors at East London College for the British Electrical and Allied Industries Research Association during 1922–23, and they desire to record their thanks for permission to make use of it.

(I) METHODS OF MEASUREMENT.

(A) GENERAL.

In the measurement of electrical quantities by direct-reading instruments, an essential function of the measuring instrument is to "convert" the electrical quantity into a form perceptible to the physical senses—usually into a mechanical motion, either of parts of the instrument itself, or controlled by it.

Such motion may take place in one, two or three dimensions. The last-named has scarcely been used: one-dimensional or linear motion is the commonest type employed: two-dimensional motion has already been used to a considerable extent, and it is hoped to show in this paper how its application is extended by modern developments in instruments.

It may be either the displacement or the velocity of the moving pointer or indicator of the instrument

which furnishes the required measure of the electrical quantity. Both are utilized, but the former is the more common.

(B) Classification of Methods.

(1) linear deflectional systems.

The usual commercial electrical instruments are of the steady-deflection type. These instruments serve to measure R.M.S. values of periodic quantities (in a.c. work), as well as steady values (as in d.c. work). By adaptation also, as in the ballistic galvanometer and electrometer, they will furnish information about transient phenomena. But for detailed study of transient quantities and also of periodic variables it is necessary to measure their instantaneous values.

In Section (II) is described the development of instruments that will measure these instantaneous values. Such instruments ("oscillographs," etc.), if used with linear deflection like the steady-deflection instruments referred to above, furnish a ready means of measuring maximum and minimum values of variable quantities,* but in general it is necessary to use them with a two-dimensional method of recording.

(2) two-dimensional systems.

Broadly speaking, the methods of indicating and recording variable electrical quantities which utilize the two-dimensional principle may be divided into two classes; these may best be denoted by the terms "oscillographic" and "cyclographic."

(*a*) *Oscillographic method.*†

The distinguishing feature of the first of these two methods is that the second component motion has as its sole function the provision of a time scale or time co-ordinate, the purpose of this on the indication or record being to render possible a study of the time-variations of the electrical quantity under investigation, as it is reproduced by the first component motion. This first component of the motion is almost invariably imposed upon the indicator of the instrument, as is done in the steady-deflection instruments previously referred to. The second component of the final relative motion is commonly imposed not on the indicator but on the chart or recording plate; this component is usually a continuous uniform motion, and may be either linear, in a direction perpendicular to the first component, or circular, with its centre on the line of action of the first component.

Included in this class are the recording instruments which use a mechanical pen-pointer in conjunction with a paper chart kept in motion by a spring motor; and many types of oscillograph which use an optical pointer, for example, in conjunction with a moving photographic plate or film. Note that in these arrangements only one of the two component motions is available for control by the electrical quantity to be studied; but this does not preclude the use of "double" and "triple" instruments, by which means simultaneous records of more than one such quantity may be superimposed on the same chart [see Section I, C, 2, (*a*)].

A second method of introducing the time-scale motion is to superimpose this on the indicator itself, using a fixed recording screen or plate; in instruments with an optical pointer this is frequently done by means of a rotating or oscillating mirror (synchronized for periodic quantities). In instruments using a "ray" or "jet" pointer the control device used for imposing the second component motion on the pointer may be of the same nature as that used for the first component —in this case, however, we really have a "cyclographic instrument" used for "oscillographic work," but this is a popular combination

(*b*) *Cyclographic method.**

The second, the "cyclographic," method of measurement utilizing the two-dimensional principle, though of more recent development than the first method, is perhaps the most potent method available for investigation of variable quantities as required in modern electrical engineering practice.

The distinguishing feature of this system is that both of the component motions (constituting the resultant relative motion of indicator and screen or chart) are under the control of variable quantities applied to the instrument. The method may be applied in a manner similar to the more usual oscillographic arrangement, viz. one component motion applied to the indicator itself, and the second component applied to the chart (in a direction perpendicular to the first). This arrangement is exemplified in mechanical engineering practice by the engine indicator and by the autographic recording apparatus applied to testing machines.

The most usual arrangement adopted in the electrical cyclograph, however, is a fixed chart or screen, the indicator having imposed upon it both of the component motions. The two control devices used for applying the two component motions to the indicator are usually of similar nature, depending, of course, on the kind of indicator employed. Thus in an electrified-jet instrument the control devices may be either magnetic fields or electric fields, or one of each. With an optical pointer, i.e. a beam of light, as indicator, the control devices are usually both oscillating mirrors, arranged to produce deflections of the light pointer mutually perpendicular. (Examples of the latter method are the arrangements of Puluj † with resonant working, and D. K. Morris and J. K. Catterson-Smith ‡ with non-resonant working.)

(C) Two-dimensional Methods Applied to Periodic Quantities.

(1) general.

One of the chief uses of the oscillogram drawn to rectangular co-ordinates is to present a picture of the variation of a quantity with time. The importance of this requirement is emphasized by the fact that frequently circular and polar oscillograms, and cyclo-

* See Bibliography, (1).

† In the oscillograph only one of the two component motions (of the indicator relative to the recording screen) is under control of an unknown variable quantity. The second component motion has as its sole function the introduction of the time co-ordinate on the record. This motion may be applied either to the recording screen or to the indicator itself.

* In the cyclograph each of the two component motions is under the control of a variable quantity applied to the instrument. Quite commonly one of these quantities is controlled so that it is a known function of time; thus the cyclogram yields the same information as an oscillogram.

† See Bibliography, (2). ‡ *Ibid.*, (3 and 4).

TABLE 1.

Methods of Measurement.

In this table various known methods of measurements are classified according to the definitions of the preceding Section I, B.

	Instruments with linear deflection, i.e. "One-dimensional"	"Two-dimensional" instruments: Oscillographic, Polar co-ordinates	"Two-dimensional" instruments: Oscillographic, Rectangular co-ordinates	"Two-dimensional" instruments: Cyclographic (rectangular co-ordinates)
Steady-deflection instruments	Ammeters, galvanometers, etc. Cathode-ray tube	(Recording pressure gauge)	Recording ammeters, etc. Recording flow-meters	(Not used)
Vibratory instruments: Resonant	Vibration galvanometer Einthoven galvanometer	(May be used for	frequency measurement)	Phase indicators [Puluj (1893) and Leyshon (1923)] Cathode-ray tube [see Braun (1906)]
Vibratory instruments: Non-resonant ..	Oscillographs, including Braun tube [MacGregor-Morris, 1902]	Mechanical oscillograph [Chubb, 1914] Non-mechanical oscillograph [Grix, 1921]	Mechanical oscillograph [Duddell, Blondel, etc.] Non-mechanical oscillograph [Dufour (1914), Watson Watt (1923), Keys (1921)]	Engine indicator, and autographic recorder Duddell instruments [D. K. Morris, 1904] Cathode-ray cyclograph [Ryan (1903), Minton (1915)]

grams when the second quantity has a known time relation, are converted by re-plotting into rectangular oscillograms.

Most forms of cyclograms and superimposed oscillograms, however, involving more than one unknown quantity (in addition to the time scale if one is used) permit the determination of "derived quantities" (such as mean and R.M.S. values of P.D. and current; energy, power, and power factor; frequency relations) by taking suitable measurements from the diagram and making the appropriate calculation on the lines indicated in the following sections.

(2) OSCILLOGRAPHIC METHOD.

(*a*) *With rectangular co-ordinates.*

Suppose that the plane of Fig. 1 represents the recording screen of an oscillograph, and that z is its

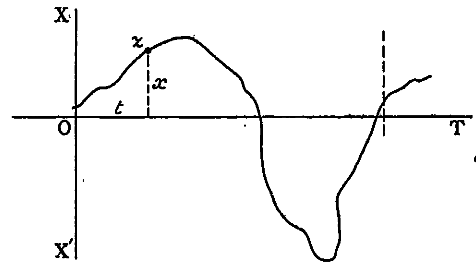


FIG. 1.—Rectangular oscillogram with linear law.

pointer or indicator. Assume also that the axis X′OX is drawn parallel to the motion of z due to the applied electrical quantity, and that the axis OT is the time axis, being the path traced by z when no electrical quantity is applied to the instrument.

Then as the oscillograph is operated by the applied periodic quantity the indicator z moves over the screen and traces out on it a periodic curve; and when the time-scale motion is made to repeat itself and is synchronized with the fundamental frequency of the unknown quantity, the curve repeats, i.e. the indicator travels over the same path again and again.

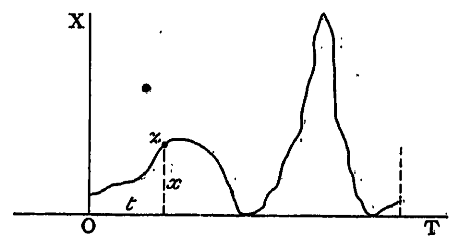


FIG. 2.—Rectangular oscillogram with square law.

Some oscillographic instruments, e.g. the electrometer of Taylor-Jones,* operate on a square law, that is, the deflection x of the pointer z is proportional to the square of the periodic quantity at every instant. Under these circumstances the deflection is never negative (see Fig. 2).

It is easy to obtain the R.M.S. value of the unknown quantity from a square-law oscillogram, for the area under the curve for a complete cycle is easily determined by planimeter, and this area, divided by the length of

* See Bibliography, (5).

the time axis corresponding to one cycle, gives a measure of the "mean square" of the quantity. Introduce the scale factor and extract the square root, and the required value is obtained.

It is not practicable, however, to use these oscillograms for mean values, or values of energy and power (with simultaneous records), primarily because of the ambiguity of sign in calculating from the square root of the measured deflection. For similar reasons ambiguous results follow in the determination of frequency relations. Thus with a "true a.c." unknown quantity (i.e. one whose mean value is zero) the lowest frequency shown by the oscillogram is double the true fundamental frequency.

However, in the majority of modern oscillographs the deflection of the indicator is proportional to the first power of the applied quantity (i.e. a linear law). In this case the area under the curve, divided by the time-period of the quantity as measured on the time scale, gives the mean value (arithmetic mean) of the quantity. But the effective value is usually the more important to determine, and for this the method

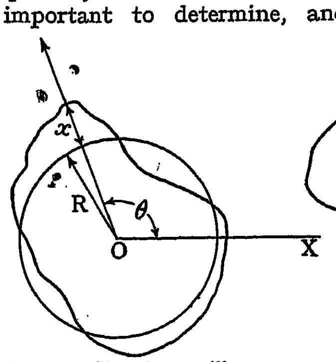


FIG. 3.—Circular oscillogram (with base circle).

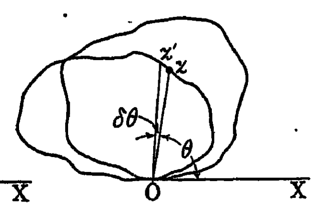


FIG. 4.—Polar oscillogram.

becomes complicated. It is necessary to replot the curve, squaring the instantaneous values (in other words, to construct a "square law" oscillogram), determine the mean of this and extract the square root as above described. Similarly in using superimposed oscillograms, to determine the mean power involves drawing a graph with ordinates at each point equal to the product of the corresponding ordinates of the two simultaneous records. The mean value of this curve is obtained as before, and both scale factors must be introduced. Having thus determined the effective values of a P.D. and a current in the same circuit and the net power flowing, the power factor (and phase-angle, of sinusoidal quantities) immediately follow.

Should the two periodic quantities be nearly alike in wave-form (as for example when both approximate sufficiently to the sinusoidal form), their phase difference may be determined directly from the record, since the scale factor of the time axis is known. From this result the power factor is easily calculated. Under these same conditions accurate determinations of frequency ratios may be made [see Section I, C, 3, (*f*)].

(*b*) *The circular oscillogram.*

When it is desired to make the instrument indicator re-trace the oscillogram regularly, the time-scale motion must be made to repeat. This can be done with the rectilinear motion, by methods to be described in Part 2 (Section VIII). But a simpler way is to use a circular motion instead—this gives rise to the circular oscillogram. Obviously an integral relation must hold between the rotational speed of the circular motion and the frequency of the periodic quantity.

Alternatively the circular oscillogram may be regarded as one constructed upon a "base circle" as time axis instead of a straight line. Thus if the plane of Fig. 3 represents the screen of the oscillograph and z its indicator, the base circle is the path traced by z when no deflecting quantity is applied. When the oscillograph is operated by an applied quantity, the path traced departs from a circle in some such manner as depicted.

Chubb * and Beliavsky † have shown how to determine the effective value of a periodic quantity from a circular oscillogram, and the power and power factor in

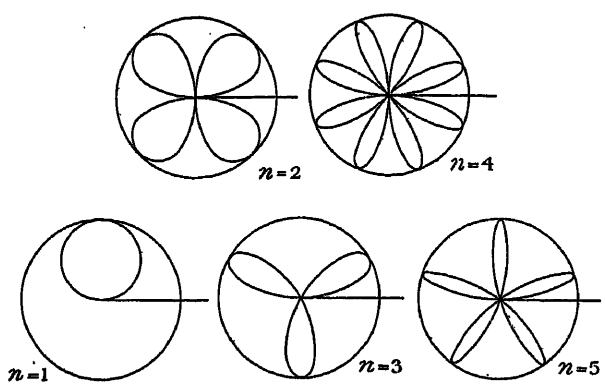


FIG. 5.—Polar oscillogram of a sinusoidal quantity, showing effect of odd and even ratios between frequency of applied quantity and that of time scale.

a circuit from the superimposed oscillograms of the P.D. and the current.

(*c*) *The polar oscillogram.*

The polar oscillogram presents the wave-form of a periodic quantity drawn to polar co-ordinates instead of to Cartesian co-ordinates; it may be regarded as a special case of the "circular oscillogram," in which the base circle has shrunk to zero. As before, let the plane of Fig. 4 represent the oscillograph screen and z the indicator. Then with the time-scale motion in operation, but with no applied quantity, the indicator remains at rest at the origin O. When the periodic quantity is applied, a curve is traced as shown, the radius vector of which is at each instant proportional to the applied quantity. The position of the indicator z may therefore be expressed in the polar co-ordinates r, θ.

The curve closes upon itself and repeats when there is an integral relation between the speed of rotation of the time-scale motion and the frequency f of the applied quantity (see Fig. 5). Thus if n cycles of the periodic quantity occur during each revolution of z, i.e. if when $\theta = 2\pi$, the time $t = nT$ (where T = periodic time = $1/f$), then

$$\theta = t \times \frac{2\pi}{nT}, \quad \text{or} \quad t \times \frac{2\pi f}{n}.$$

* See Bibliography, (0). † *Ibid.*, (7).

Under this condition it is possible to measure with planimeter the area swept out by the radius vector for each revolution of the indicator. The meaning of this measurement may be interpreted as follows *:— Suppose the area to be divided into elemental sectors, each having a central angle $\partial\theta$, and a radius r (the value corresponding to angle θ). Each element may be regarded as a triangle, and its area may be written

$$\partial A = \tfrac{1}{2} \times r\partial\theta \times r = \tfrac{1}{2}r^2\partial\theta$$

By summation in the limit when $\partial\theta$ is infinitely small, the whole area is

$$A = \int_0^{2\pi} \tfrac{1}{2}r^2\partial\theta$$

Now r, being proportional to the applied quantity, is a function of time; the area may therefore be expressed as a time integral instead of as a space integral, thus—

$$A = \int_0^T \tfrac{1}{2}r^2\left(\partial t \times \frac{2\pi}{nT}\right) = \frac{\pi}{nT}\int_0^T r^2\partial t$$

From this it will be seen that the area gives a measure of the "mean square" of the periodic quantity. Therefore by introducing the calibration constant of the instrument and extracting the square root, the effective value is obtained.

Using superimposed oscillograms of P.D. and current, the power and power factor in a circuit may be determined by an ingenious method that has been described

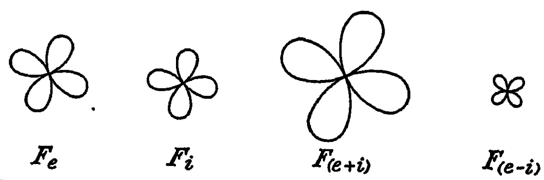


FIG. 6.—Superimposed polar oscillograms (after Grix).

by Chubb,† Grix,‡ and others in the following way:— Oscillograms are taken not only with the P.D. and the current acting separately, but also with them acting together and in opposition. This gives four curves (see Fig. 6) the areas of which may be designated as follows:—

$$A_e,\ A_i,\ A_{e+i},\ A_{e-i}$$

If therefore K_e and K_i are the calibration constants for the P.D. and the current deflections respectively, then

$$A_e = \frac{\pi}{nT}\int_0^T (K_e e)^2\partial t = K_e^2\frac{\pi}{nT}\int_0^T e^2\partial t$$

$$A_i = \frac{\pi}{nT}\int_0^T (K_i i)^2\partial t = K_i^2\frac{\pi}{nT}\int_0^T i^2\partial t$$

$$A_{e+i} = \frac{\pi}{nT}\int_0^T (K_e e + K_i i)^2\partial t$$

$$= K_e^2\frac{\pi}{nT}\int_0^T e^2\partial t + K_i^2\frac{\pi}{nT}\int_0^T i^2\partial t + 2K_eK_i\frac{\pi}{nT}\int_0^T ei\partial t$$

$$A_{e-i} = \frac{\pi}{nT}\int_0^T (K_e e - K_i i)^2\partial t$$

$$= K_e^2\frac{\pi}{nT}\int_0^T e^2\partial t + K_i^2\frac{\pi}{nT}\int_0^T i^2\partial t - 2K_eK_i\frac{\pi}{nT}\int_0^T ei\partial t$$

* Also see Bibliography, (8). † *Ibid.*, (6). ‡ *Ibid.*, (9).

From these results it is possible to separate the term

$$2K_eK_i\frac{\pi}{nT}\int_0^T ei\partial t$$

Now the power consumed in the circuit is the mean value of ei (the instantaneous power) taken over a complete cycle, and therefore

$$\text{Power } (P) = \frac{1}{T}\int_0^T ei\partial t$$

The result then may be stated, that

$$\text{Power } (P) = \frac{n}{2K_eK_i\pi}\{A_{e+i} - (A_e + A_i)\} \quad . \quad (1)$$

or

$$P = \frac{n}{2K_eK_i\pi}\{A_e + A_i - A_{e-i}\} \quad . \quad . \quad (2)$$

or

$$P = \frac{n}{4K_eK_i\pi}\{A_{e+i} - A_{e-i}\} \quad . \quad . \quad . \quad (3)$$

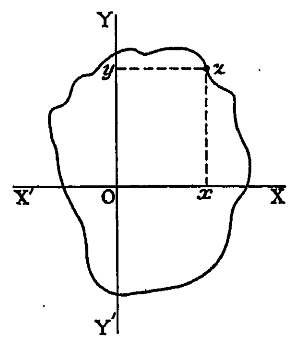


FIG. 7.—General cyclogram.

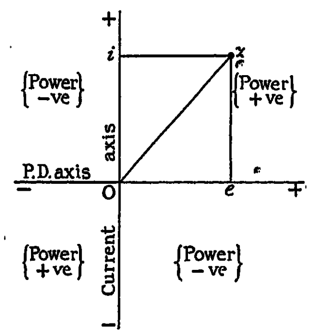


FIG. 8.—Cyclogram of P.D. and current.

The apparent power is the product of the effective values of the P.D. and the current, and is therefore given by

$$\sqrt{\left(\frac{1}{T}\int_0^T e^2\partial t\right)} \times \sqrt{\left(\frac{1}{T}\int_0^T i^2\partial t\right)} = \sqrt{\left(\frac{n}{\pi K_e^2}A_e\right)} \times \sqrt{\left(\frac{n}{\pi K_i^2}A_i\right)}$$

$$= \frac{n\sqrt{(A_eA_i)}}{\pi K_eK_i}$$

and the power factor is the quotient, so, using (3) above, we get

$$\text{Power factor} = \frac{1}{4}\left\{\frac{A_{e+i} - A_{e-i}}{\sqrt{(A_eA_i)}}\right\}$$

(3) CYCLOGRAPHIC METHOD.

(*a*) *General.*

Suppose that the plane of Fig. 7 represents the screen of a cyclograph, of which z is the indicator, and that the axes X'OX, Y'OY are drawn parallel to the two components of the motion of z (each being due to one of the applied quantities), their origin O being the position of rest of the indicator z.

As the cyclograph is operated by the applied periodic quantities, the indicator z moves about over the screen and traces out on it a periodic curve; and when the

quantities have an integral frequency ratio this curve closes upon itself and repeats.

(b) *Properties of the cyclogram.*

(i) *The deflections.*—A common use for the cyclograph is to study the power consumption or other electrical property of an apparatus, or, in general, the relations between a P.D. and a current. Each of these two quantities then will operate one of the component deflections of the indicator, in other words

$$x = K_e \times e$$
and
$$y = K_i \times i$$

where K_e, K_i are the calibration constants of the instrument.

(ii) *Resistance.*—At each instant

$$e/i = r$$

where r is the instantaneous resistance corresponding to the values e and i of the P.D. and current respectively. This derived quantity r is equal to $(x/K_e) \div (y/K_i)$ on the cyclogram (Fig. 8) and it is therefore inversely proportional to the slope of the radius vector from the origin O to the indicator point z.

(iii) *Power.*—Again, since electrical power is measured by the appropriate values of P.D. and current, we have

$$\text{Power } (p) = e \times i$$

This is equal to $(x/K_e) \times (y/K_i)$ and is therefore proportional to the area of the rectangle O*ezi* on the cyclogram. Note, however, that this derived quantity p is the instantaneous value of the power flowing into or out from the apparatus, and holds only for the same instant of time as the instantaneous values e and i.

The sign of this quantity p depends solely on the signs of its two factors e and i. Thus when the indicator z is in the upper right-hand quadrant of the cyclogram (see Fig. 8) the instantaneous power is positive; similarly when z is in the opposite quadrant (bottom left-hand) the power is also positive, i.e. flowing in the same sense; but when z is in either of the two remaining quadrants the power is negative, i.e. flowing in the opposite sense.

In order to obtain the average power it is necessary to evaluate the variations of p for one cycle, integrate with respect to time and divide by the time period, just as with the oscillographic method using rectangular co-ordinates. The quantities power factor and phase angle (in the case of sinusoidal variables) follow in the usual manner.

In power measurement then it is evident that the cyclographic method has so far offered no advantages over the oscillographic method (other than showing changes in sign of the instantaneous power, and therefore the presence or absence of surging energy).

(c) *The area of the cyclogram.*

It has been shown that when the cyclograph is operated by periodic quantities of equal frequency, for example, a closed curve is traced by the indicator. Such a figure encloses a definite area; and it is possible, by correct choice of the quantities used to control the deflections x and y, to make the value of this area represent one of the required results.

In Fig. 9 the diagram traced by the indicator is shown. Suppose it is divided into a number of "elemental strips"; then the area of each strip may be expressed in the form

$$\partial A = y\partial x$$

where y is the length of the strip and ∂x its width. Then the whole area A is the summation of the areas of all the elemental strips, covering a complete cycle of the motion of z. Thus $A = \int y\partial x$ between the limits of one cycle.

If the division of the area into its elemental strips were made parallel to the X-axis instead of parallel to the Y-axis (as in Fig. 10), then by similar reasoning we obtain $A = \int x\partial y$ between the limits of one cycle.

It has been specified for these results that the quantities x and y are periodic functions of time. The

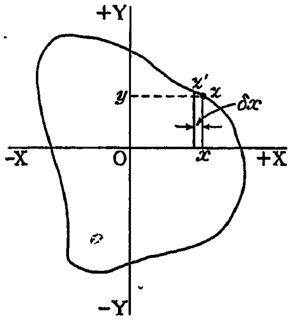


FIG. 9.—Area of a cyclogram.

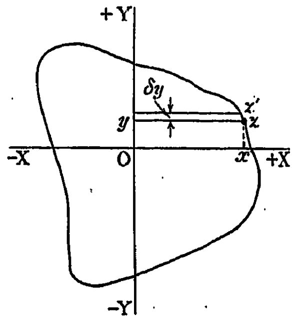


FIG. 10.—Area of a cyclogram. Alternative integration.

area A may therefore be expressed as a time integral instead of as a space integral. Thus

$$A = \int y\partial x$$
$$= \int_0^T y\frac{\partial x}{\partial t}\partial t$$

where T is the time period of one cycle. A similar result is obtained by using the alternative expression

$$A = \int x\partial y$$
$$= \int_0^T x\frac{\partial y}{\partial t}\partial t$$

(d) *Application to power measurement.*

From the foregoing analysis it is apparent that the cyclograph gives automatically an integration with respect to time of the instantaneous product of the two factors y and $\partial x/\partial t$ (or, in the alternative expression, the factors x and $\partial y/\partial t$). This property of the cyclograph may be utilized to give directly (i.e. without any intermediate plotting or calculation) the energy per cycle, and hence the mean power consumed in the apparatus—the necessary condition is that the instantaneous value of the product $y(\partial x/\partial t)$ [or, in the alternative scheme, of the product $x(\partial y/\partial t)$] shall truly represent the instantaneous power in the apparatus.

Suppose now we have chosen one of the components,

say y, to be proportional to the P.D. Then in order to produce the above result we find by simple division that the quantity $\partial x/\partial t$ must be proportional to the current. It follows from this that the second component deflection, x, must be proportional to the time integral of the current, since $x = \int(\partial x/\partial t)\partial t$. Similarly, if we have chosen one of the components to be proportional to the current, it may be shown that the second component must be made proportional to the time integral of the P.D.

It is important to note that, as a result of this choice of the component deflections, the quantity represented by area on the cyclogram is energy; for it is the product of the two deflections, and with either choice of deflections this product is found to be the time integral of power, which is energy. Thus with periodic quantities of equal frequency, the area of the cyclogram figure, which is the net value of the area swept out by the cyclograph indicator during one cycle, represents the net energy passed into the apparatus per cycle. This energy per cycle, divided by the time period (or multiplied by the frequency), gives the mean power consumed in the apparatus. The simplicity of this process—measure an area, introduce the calibration constants, multiply by the frequency—constitutes the great merit of the cyclographic method for power measurement.

(*e*) *The cyclograph as a power-factor meter.*

(i) *Sinusoidal quantities.*—A special case in the determination of power factor from a cyclogram demands attention, viz. when the periodic quantities of equal frequency have a sinusoidal wave-form. In this case, then, we have

$$e = E_m \sin 2\pi ft$$
$$i = I_m \sin (2\pi ft + \phi)$$

where ϕ expresses the phase difference between the two quantities (in terms of the phase angle between their vectors), and E_m and I_m are the maximum values of the P.D. and the current respectively.

(ii) *High power factor.*—If these two quantities directly control the two component deflections of the cyclograph [as suggested in Section I, C, 3, (*b*)], then

$$x = K_e e = K_e E_m \sin 2\pi ft$$
$$y = K_i i = K_i I_m \sin (2\pi ft + \phi)$$

The cyclogram obtained is thus a "Lissajous figure," and in the particular case chosen of equal frequencies it is an ellipse (see Fig. 11).

Note that the maximum abscissæ and maximum ordinates of this ellipse are

$$\pm X = \pm K_e E_m$$
and
$$\pm Y = \pm K_i I_m$$

respectively, i.e. the ellipse is bounded by a rectangle of total length $2X$ and total width $2Y$.

A further property now reveals itself, viz. that when $x = 0$, then $\sin 2\pi ft = 0$, and $2\pi ft = 0$ or π, etc.

Therefore $$y_0 = \pm K_i I_m \sin (2\pi ft + \phi)$$
$$= \pm K_i I_m \sin \phi \quad \text{or} \quad \pm Y \sin \phi$$

Similarly when $y = 0$,
$$x_0 = \pm X \sin \phi$$

Therefore the ratio (intercept of ellipse)/(intercept of rectangle) on either axis is equal to $\sin \phi$. From this, $\cos \phi$, the power factor, is easily determined.

The method is most accurate and most sensitive when the ellipse is narrow, as shown in Fig. 11. In the limit when the ellipse becomes the diagonal of the rectangle,

$$x_0 = 0$$

whence $\sin \phi = 0$ and $\cos \phi$ or power factor $= 1$. This arrangement, then, is the better adapted for use in a.c. power engineering for measuring departure from unity power factor.

(iii) *Low power factor.*—In measuring power losses cases frequently arise where the power factor must be accurately determined when it is in the neighbourhood of zero. For this work it is better to use the mode

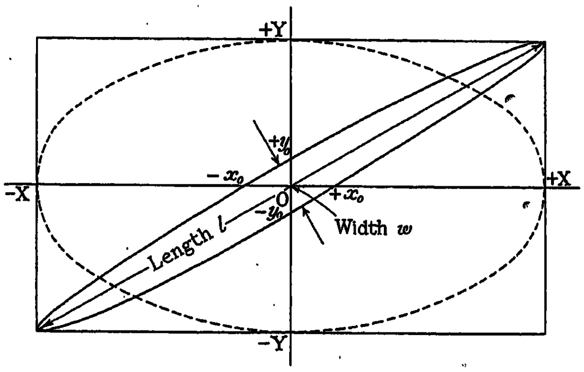


FIG. 11.—Elliptical cyclogram (power-factor determination).

of operation of the cyclograph described in Section I, C, 3, (*d*). Here

$$y = K_i I_m \sin (2\pi ft + \phi)$$
and
$$\frac{\partial x}{\partial t} = K_e E_m \sin 2\pi ft$$
whence
$$x = \int K_e E_m \sin 2\pi ft \partial t$$
$$= -2\pi f K_e E_m \cos 2\pi ft$$

Then when

$$x = 0, \quad \cos 2\pi ft = 0, \quad \text{and} \quad 2\pi ft = \frac{\pi}{2}, \frac{3\pi}{2}, \text{etc.}$$

$$\therefore y_0 = K_i I_m \sin\left(\frac{\pi}{2} + \phi\right)$$
$$= \pm K_i I_m \cos \phi \quad \text{or} \quad \pm Y \cos \phi$$

and by similar reasoning, when $y = 0$,

$$x_0 = \pm X \cos \phi$$

Therefore in this case the ratio (intercept of ellipse)/(intercept of rectangle) on either axis is equal to $\cos \phi$, i.e. the power factor itself.

As before, the method is most sensitive when the ellipse is narrow; in the limit, $x_0 = 0$, giving $\cos \phi = 0$ or power factor zero.

(iv) *Alternative methods.*—When the cyclogram is a narrow ellipse it is sometimes more convenient to measure

its major and minor axes (l and w respectively). Their product gives a measure of the area of the ellipse, and the power factor may be evaluated as the ratio of this area to that of the maximum ellipse that can be contained in the bounding rectangle (i.e. corresponding to unity power factor).

$$\text{Power factor} = \frac{\pi wl}{\pi(2X)(2Y)} = \frac{wl}{4XY}$$

Note that, as in the previous methods, the calibration constants are not required.

An alternative method is to measure the "fineness ratio" of the ellipse, i.e. the ratio of its major and minor axes. When the ellipse is sufficiently narrow [i.e. power factor very small with method (iii) above], the major axis may be taken as equal to the diagonal of the bounding rectangle, or

$$l = 2\sqrt{(X^2 + Y^2)}$$

The geometry of the figure also gives the minor axis as

$$w = \frac{2XY}{\sqrt{(X^2 + Y^2)}} \cos \phi$$

Then the fineness ratio becomes

$$\frac{w}{l} = \frac{XY}{X^2 + Y^2} \cos \phi = \frac{r}{1 + r^2} \cos \phi$$

where $r = Y/X$.

If the two maximum deflections of the indicator can be made equal, i.e. $r = 1$, the expression simplifies as follows:—

$$\frac{w}{l} = \frac{1}{2} \cos \phi$$

whence power factor $= \cos \phi = 2\frac{w}{l}$.

(v) *Partial recording.*—With the above methods of determining power factor from the cyclogram, "partial recording" [see Section VIII, A, 3, (*a*), (i)] may be practised—for if the two tips and the middle slice of the ellipse, and one axis, are recorded, the power factor is determinable. In fact, with the second method under (iv) above, if the cyclograph is adjustable in sensitivity so that constant maximum deflection of the indicator is used, then $r = 1$, and l is constant, so a measurement of one linear dimension (w) is sufficient to determine the result.

(*f*) *Frequency ratios.*

(i) *Absolute measurement of frequency.*—From Section I, C, 2 it is evident that, provided the absolute velocity (as well as the form of variation) of the time-scale motion is known, any oscillogram will furnish sufficient data for determining the time period of the unknown quantity and hence its frequency.

(ii) *Stroboscopic method.*—Stress has been laid upon the necessity for an integral ratio between the frequencies of the two component motions, both with oscillographs (see also Section VIII) and with cyclographs, in order that the indicator when it repeats its cycle shall follow exactly the original path, so producing a stationary diagram. Very slight departure from this condition causes a progressive change in the

TABLE 2.*

Power Measurement Methods.

Provided that suitably-designed instruments are used, the methods in this table are applicable to high frequencies (up to and including radio frequencies).

Method	Measured quantities				Calculated quantity		Remarks
	First	Second	Third				
	E.M.F. or P.D.	Current	Name	—	Name	—	
1. Steady-deflection instruments alone	Electrostatic voltmeter reading True R.M.S. value, independent of wave-form	Hot-wire ammeter reading True R.M.S. value, independent of wave-form	Power	Electrostatic wattmeter reading True value, independent of wave-form	Power factor	True value, independent of wave-form	No information of wave-form given Fails to indicate quick changes in conditions of test
2. Electron-jet cyclograph alone (calibrated)	Maximum component deflection Maximum value only, dependent on wave-form	Maximum component deflection Maximum value only, dependent on wave-form	Power	Area of cyclogram True value, independent of wave-form	Power factor	Dependent on wave-form	Indicates wave-form, and shows instantaneous behaviour of the test apparatus
3. Electron-jet cyclograph as wattmeter only (calibrated)	Electrostatic voltmeter reading True R.M.S. value, independent of wave-form	Hot-wire ammeter reading True R.M.S. value, independent of wave-form	Power	Area of cyclogram True value, independent of wave-form	Power factor	True value, independent of wave-form	Indicates wave-form, and shows instantaneous behaviour of the test apparatus
4. Electron-jet cyclograph as power-factor meter only (not calibrated)	Electrostatic voltmeter reading True R.M.S. value, independent of wave-form	Hot-wire ammeter reading True R.M.S. value, independent of wave-form	Power factor	"Shape" (ratio of linear dimensions) of cyclogram Dependent on wave-form	Power	Dependent on wave-form	Indicates wave-form, and shows instantaneous behaviour of the test apparatus

* Extracted from a Report to the British Electrical and Allied Industries Research Association.

phase relation of the two motions, and as a result the form of the diagram changes, "precessing" through a complete cycle of changes for each cycle (of the lower frequency) by which the phase relation alters. Hence by determining the rate (frequency) of precession in the diagram, we obtain the change of frequency necessary to restore the integral ratio; when this ratio is unity the rate of precession measures the absolute difference between the two frequencies. The method has no frequency limitation (beyond that of the instruments used); and the higher the frequencies under investigation the more sensitive does the method become.

When the quantities studied are sinusoidal, the cyclograph gives the well-known "Lissajous" figures; from the form of the figure it is possible to determine the value of the frequency ratio in use.

(II) DEVELOPMENT OF INSTRUMENTS FOR DELINEATING RAPIDLY VARYING QUANTITIES.

(A) STEADY-DEFLECTION INSTRUMENTS.

To perform its function of "converting" an electrical quantity to be measured into a physical form that is directly perceptible to the physical senses, an electrical measuring instrument must utilize one of the physical phenomena that accompany electricity, for example, the electrostatic, the electromagnetic, the thermal, or the optical effects due to magnetic or electric fields, combined perhaps with pyro-electric, piezo-electric, or other thermal or optical phenomena. It is the appropriate choice of its principle of operation that determines the ability of a steady-deflection instrument to indicate any required function of a varying quantity. On this choice also, and on the mechanical design of the instrument, depends its "law," i.e. the relation between the reading or indication and the quantity measured (whether it be linear, square, or otherwise).

(B) MECHANICAL DELINEATING INSTRUMENTS.

(1) THE NEED FOR VIBRATORY INSTRUMENTS.

In the measurement of periodic quantities it was soon found that more information was required than was given, for example, by the "virtual values." A knowledge of "wave-form" became necessary in order that the growing problems of alternating-current engineering could be solved. By means of the "point by point" method, used first by Lenz (1849) and developed by Joubert * (1880), Rosa † (1898), Hospitalier ‡ (1903), and Lübcke § (1917, with an electron-jet instrument), it was made possible to study the wave-forms of periodic quantities while using only steady-deflection instruments. The method, however, requires much auxiliary apparatus and (with the exception of Lübcke's application) this includes a synchronous commutator, which limits its use to the lower frequencies; it is necessary also for the quantity studied to repeat itself with close accuracy for the considerable time occupied by the test.

* See Bibliography, (10 and 11). † *Ibid.*, (12).
‡ *Ibid.*, (13). § *Ibid.*, (14).

From these considerations it will be seen how great advantage may be derived from the use of an instrument whose indicator will follow the variations of a periodic quantity, and hence give an indication or record of the wave-form.

For the study of transient phenomena the use of an instrument of this description is usually the only solution.

(2) THE RESONANT TYPE.

Wien * (1891) suggested the use of the resonance principle to increase the sensitivity of detectors used in a.c. bridge measurements. The idea was realized in his "optical telephone," and was developed into the vibration galvanometer by Wien (1891), Rubens (1895), Campbell (1907), Duddell (1907), and Drysdale (1912). The string galvanometer of Einthoven † has also been used as a resonance instrument for both low frequencies and radio frequencies (in 1923). ‡

The cyclographic method (two-dimensional) also has been adapted to phase measurements with Lissajous figures by Puluj § (1893), who used two resonant "phase-indicators" acting on the same optical pointer, and by Miss Leyshon ‖ (1923), who used a single instrument.

(3) THE NON-RESONANT TYPE.

Frölich ¶ (1887) first attempted to produce an instrument for wave-form delineation, based on the telephone receiver; the device was improved upon by E. Thomson** (1888), Guyau †† (1913), and Dubois ‡‡ (1923), but like Wien's apparatus it manifests the resonance effect, which, combined with insufficient damping, distorts the wave-form.

An instrument on the lines of the d'Arsonval galvanometer (moving-coil type) was devised by Moler §§ (1892) which he called a "dynamo indicator" by analogy with the steam-engine indicator. The records were traced on a revolving smoked drum; the natural frequency of the instrument was 103 cycles per sec.

Blondel ‖‖ (1891) was the first definitely to state the conditions under which a galvanometer would follow the variations of a periodic quantity sufficiently accurately:—

- (i) High "natural frequency" of oscillation, as great as 50 times that of the phenomenon to be investigated.
- (ii) Damping in the neighbourhood of the "critical value."
- (iii) Self-induction as small as possible.
- (iv) Negligible hysteresis and eddy-current effects.
- (v) Adequate sensitivity.

Blondel's first instrument ¶¶ to fulfil these requirements, called by him an "oscillograph," was of the "moving-iron" type; in its latest form it has a natural frequency of about 40 000 cycles per sec.

Blondel also suggested (1891) the use of the "moving-

* See Bibliography, (15). † *Ibid.*, (16). ‡ *Ibid.*, (17).
§ *Ibid.*, (2). ‖ *Ibid.*, (18). ¶ *Ibid.*, (19).
** *Ibid.*, (20). †† *Ibid.*, (21). ‡‡ *Ibid.*, (22).
§§ *Ibid.*, (23 and 24). ‖‖ *Ibid.*, (25). ¶¶ *Ibid.*, (26).

coil" principle, and this was applied by Duddell * in his "bifilar" instrument; this attains a natural frequency of 12 000 cycles per sec. but has much smaller self-inductance.

These two types of instrument have been of great use for commercial oscillographic work at low frequencies. Both types carry a mirror on their moving parts, for controlling the motion of an optical pointer.

In the Ganz oscillograph the mirror is eliminated, by using a single vibrating strip with microscopic projection for indicating and recording, as in the Einthoven "string" galvanometer. The instrument has a natural frequency of up to 5 000 cycles per sec. and has the advantage of robustness and portability.

Janet † (1894) proposed a chemical method of recording wave-forms on a drum rotating at synchronous speed, and Burch ‡ (1896) suggested the use of the capillary electrometer for a similar purpose. Such methods are necessarily limited to power frequencies, and neither saw commercial development.

A hot-wire oscillograph has been devised by Irwin § (1908); but though it is applicable to power circuits with the help of a special phase-advancer to compensate for the thermal lag, the hot wire alone will not respond accurately to frequencies higher than 5 cycles per sec.

Following upon Taylor-Jones's "short-period electrometer," ‖ produced in 1907 for studying slow oscillations (up to a few hundred cycles per sec.), Ho and Koto ¶ (1913) produced their electrostatic oscillograph. This instrument has a bipolar moving system with mirror like the Duddell instrument, and so has similar damping characteristics and natural frequency (3 300 cycles per sec.); but it is operated by pure electrostatic attraction and is more suitable for high-tension work.

(4) The Limitations of Mechanical Oscillographs.

The types of instrument so far described still use some form of mechanical moving part as the deflectional element, even though the mechanical pointer which serves so well in steady-deflection apparatus has been replaced by an optical device. From this point of view there is no difference of principle between the modern mechanical oscillograph and the early telephone adaptations. Apart from the question of damping, the difference is just one of frequency range.

Blondel,** in developing the theory of the oscillograph whose natural frequency is *above* the range of the frequencies under investigation, showed that there is a definite error in the indication which grows as the frequencies approach one another. For a sinusoidal periodic quantity whose frequency is f, the indicated value falls short of the true instantaneous value in the ratio

$$\frac{\text{Indicated value}}{\text{True value}} = R = \frac{1}{1 + (f/f_0)^2}$$

where f_0 is the natural frequency of the oscillograph.

Then if the error is expressed as a fraction of the indicated value (which is permissible when the error is small) this gives

$$\text{Error } \delta = (1/R) - 1 = (f/f_0)^2$$

Hence, having decided upon the degree of accuracy necessary, the frequency limit of any oscillograph of this type may be determined.

In addition to this magnitude error, the frequency effect includes a phase displacement; but in practice this introduces no error of importance.

In investigating non-sinusoidal and transient quantities, the formulæ given are applicable individually to each sinusoidal component or harmonic present.

No instrument has been developed for measurement purposes having its natural frequency *below* the range of frequencies under investigation; the arrangement is impracticable because of the extremely small sensitivity obtainable. (It may be noted in passing that the idea has been applied to microphones for radio-telephony—here the insensitivity may be countered by amplification.)

(C) Non-mechanical Instruments.

(1) Optical Method.

It is a natural outcome of the use of the optical pointer to consider whether the control of its motion can be obtained without the use of a mechanical moving element, for if so it may be possible to eliminate the frequency limitation of the mechanical oscillograph. In a measure this was accomplished by Pionchon * and Crehore † (1895). The principle utilized is that of the rotation of the plane of polarization of a beam of polarized light traversing carbon bisulphide solution, when immersed in a longitudinal magnetic field. The amount of rotation is indicated by the position of a dark patch on a spectrum, its displacement from its initial position being proportional to the current producing the magnetic field.

The frequency limitation of such an apparatus is imposed only by the response of the carbon bisulphide molecules to the magnetic field, and should cover most electrical engineering requirements. Unfortunately, the solenoid producing the field will have a high inductance; and in addition the sensitivity of the apparatus and the definition of the dark patch "indicator" are very poor, and the apparatus has not been further developed for oscillographic work.

(2) Use of the "Jet" Principle.

A new method, suggested by E. F. Northrup, was experimented upon by Nichols ‡ (1893). The arrangement used was a column of mercury falling vertically from a nozzle supplied by a reservoir. Electrostatic deflection of the mercury jet was tried by two electrodes connected to a Holtz machine, but the apparatus was rather insensitive. Then the jet was placed in a constant horizontal magnetic field, the alternating current to be measured was passed along the jet, and visible deflection resulted. An oscillograph record was obtained on a falling plate, a camera lens giving an image of the position of the jet as it appeared behind a horizontal slit.

* See Bibliography, (27). † *Ibid.*, (28). ‡ *Ibid.*, (29).
§ *Ibid.*, (30). ‖ *Ibid.*, (5). ¶ *Ibid.*, (31 and 32).
** *Ibid.*, (26).

* See Bibliography, (33). † *Ibid.*, (34). ‡ *Ibid.*, (35).

The method was not further developed, but Nichols states that it was introduced "to show that increased accuracy of record may be looked for as the result of reducing in any practicable manner the mass of the indicating device" (page 68 of the paper referred to). We shall see, however, that in this apparatus the reduction of mass, which is not great, is not the cause of its faithful reproduction—it is inherent in the use of the jet principle.

In this apparatus the operating principle is seen to be the mechanical force experienced by a current-carrying conductor placed in a magnetic field, just as in the moving-coil instrument, the Duddell oscillograph or, to take a closer analogy, the Einthoven galvanometer. In these instruments the conductor is rigid and does not move out of the field, so that motion of the conductor takes place more or less as a whole, although the force acting on it is distributed. If the conductor were supported without constraint, then, due to its finite mass, it would move so that its acceleration at any instant was proportional to the resultant force. As a general rule, however, this force is a measure of the electrical quantity under investigation; and by constraining the conductor with an elastic restoring force (usually a mechanical spring) the motion is made such that the displacement of the conductor gives the required measure of the applied quantity.

These conditions, of a finite mass constrained by an elastic force ("elastance"), give inherently a mechanical oscillatory system; and it is from this fact that the problems of natural frequency and resonance arise.

It is important to note that with the jet device the action is quite different from that of a rigid conductor, for although the principle upon which the deflecting force depends is identical (in Nichols's arrangement, for example) there is no elastic constraining force. In spite of this absence, however, we see from the formula

$$Y = \frac{\sigma}{\rho} \cdot \frac{LD}{v^2} *$$

that at any point within the region of action of the deflecting force, the deflection (Y, lateral displacement) is proportional to the deflecting force (σ, force per unit length), the others factors being constants of the apparatus. In other words, the electrical quantity is "converted" into a mechanical deflection without the use of a mechanical oscillatory system.

There is nevertheless a frequency limitation with the jet instrument;* it is shown in the Appendix that the frequency error is equal to a fraction $\left(1 - \frac{v}{\pi f x} \sin \frac{\pi f x}{v}\right)$ of the true value, where v is the jet velocity, x the distance it travels under the deflecting force before observation, and f the frequency of the variable studied. (With the electron jet this limit may be made well outside electrical engineering requirements.)

It may be emphasized here that the mass of the jet (ρ, linear mass density) has no influence on the frequency characteristic of the instrument, because with any substance that will form a jet there will be no appreciable rigidity, i.e. the shear force between one element of length and its neighbour will be negligible.

* See Appendix XI, A, 1, (a), (ii).

(III) PRODUCTION OF CATHODE RAYS IN THE VACUUM DISCHARGE.

(A) ELECTRIC DISCHARGE IN GASES UNDER REDUCED PRESSURE.

(1) PHENOMENA OF THE GASEOUS DISCHARGE.

(*a*) *First reduction of pressure.*

Although air and other gases are usually regarded as perfect insulators, it was shown by Coulomb * (1785) that air conducts electricity very slightly at normal (atmospheric) pressure and temperature, even with low values of electric stress; this conduction is often referred to as the "dark discharge." Under increasing electric stress, the conduction phenomenon changes character, becoming successively the "glow," the "brush" (or "corona"), the "spark," and the "arc" discharge. Although the last four are accompanied by phenomena (e.g. the production of light and sound) capable of detection independently of the electrical effect, practically no use has been made of the fact for the direct measurement of varying electrical quantities. The spark discharge has, however, been used frequently for recording time intervals.

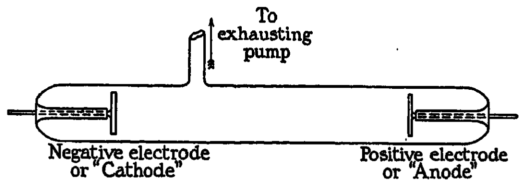


FIG. 12.—Discharge tube for exhibiting electric discharge phenomena in rarefied air.

There are other ways than increase of electrical stress by which a gas may be made to carry an electric current; chief of these is reduction of pressure of the gas. The phenomena accompanying the conduction of electricity through gases under reduced pressure are known to physicists and to those electrical engineers who deal with vacuum discharge apparatus; it is convenient, however, to describe them here in order that we may note in what ways they may be applied to the purposes of electrical measurements, and what are the unique advantages they possess for these purposes in the light of modern requirements.

A closed glass tube (see Fig. 12) with a metal disc electrode sealed into each end, and connected to a vacuum pump, is a suitable apparatus for the study of these phenomena. On the first reduction of pressure it is found that a form of spark discharge will pass which has lost the noisy character of that in free air, and which requires for its production a much smaller value of P.D. applied between electrodes. This discharge soon changes into a "bundle of sinuous and irregular streamers"; these in turn broaden out and after a considerable reduction of pressure of the air in the discharge tube (approaching 1/100th of its original value) the bulk of the tube is seen to be filled with a pink diffuse glow. For this "glow discharge" the P.D. required is only a few hundred volts, so that the

* See Bibliography, (36).

alternative spark-gap of the tube is only a fraction of a centimetre (see Table 3).

(*b*) *The Geissler discharge.*

The glow discharge retains its principal characteristic of luminosity in the gas over a considerable range of pressures. As the pressure of the gas is reduced, however, changes occur in the distribution and intensity of the glow in the discharge tube; these effects are commonly referred to as the Geissler discharges, which Townsend * classifies into four main types:—

First type.—At pressures slightly less than that mentioned, i.e. in the neighbourhood of 1/200th of atmospheric pressure, it is found that a relatively much smaller P.D. suffices to cause a discharge. Under these conditions each electrode is seen to be covered, or partially covered, by a layer of glow; the remainder of the discharge tube is dark.

Second type.—As the pressure reaches the neighbourhood of 1/1 000th atmosphere the two glows extend from the electrodes into the tube. That at the cathode or negative electrode grows to a centimetre or so in thickness, and is known as the "negative glow." That at the anode or positive electrode fills the tube, whatever its length, to within a few centimetres of the cathode; this is called the "positive column." The region between these glows is non-luminous, and is called the "Faraday dark space." In air the positive column is pink, and the negative glow a milky blue.

Third type.—As the pressure of the air is reduced to about 1/3 000th atmosphere the positive column tends to break up into button-shaped portions, called "striæ"; these are regularly spaced and have their convex sides facing the cathode. Meanwhile the positive column has shrunk in length, the remaining portions of the discharge expanding. At this stage the walls of the discharge tube are seen to fluoresce with an olive-green

TABLE 3.†

Geissler Discharge P.D.'s.

Discharge tube as in Fig. 12. Distance between electrodes, 22 cm. Diameter of electrodes, 3 cm. Tube containing air under reduced pressure.

Pressure, in atmospheres	P.D., in volts
0·0053	650
0·0037	620
0·0022	500
0·00137	470
0·00087	490
0·00053	530
0·00038	590
0·00032	630
0·00022	740
0·00017	800

* See Bibliography, (38). † *Ibid.*, (37).

TABLE 4.—*Gaseous Discharge Phenomena.*

Approximate gas pressure, in millionths of an atmosphere	Phenomena in air
	Spark discharge loses its noisy character, and is replaced by sinuous irregular "streamers" which broaden out and fill the tube with a pink diffuse "glow."
	"Geissler" discharges.
	1ST TYPE.
5 000–10 000	Gas is now highly conducting—discharge may be passed with a few hundred volts. Each electrode partially covered by a layer of glow—rest of tube dark.
	2ND TYPE.
2 000–5 000	The two glows extend outwards into the tube—"negative glow," milky blue, about 1 cm thick; "positive column," pink, fills tube to within a few cm of the cathode; two glows are separated by the "Faraday dark space." The gas is passing its point of maximum conductance.
	3RD TYPE.
1 000–2 000	Positive column tends to break up into "striæ," which thicken and then diminish in number, intensity and extent.
500–1 000	Walls of tube fluoresce (olive-green if soda glass, bluish-green if lead glass) due to "discharge rays."
	4TH TYPE.
200–500	Negative glow detaches itself from the cathode like a shell—being separated from it by the "Crookes dark space." A new velvety film ("cathode glow") spreads over the cathode surface.
100–200	Phenomena at cathode expand at expense of the rest. Positive column disappears, but a thin "anode glow" persists. Negative glow finally loses all luminosity.
10–100	Anode glow disappears, and cathode dark space expands, until eventually it fills the tube, the gas as a whole being non-luminous.
1–10	Glass walls show a bright fluorescence due to bombardment by "cathode rays" (with soda glass, apple-green, familiar from X-ray tubes). The conductance of the tube has been diminishing, until, at this point, many kilovolts are required to pass the discharge. Fluorescence diminishes, and finally tube ceases to conduct.

light (if of soda glass; lead glass gives a bluish-green), which J. J. Thomson * has shown to be due to extremely active ultra-violet radiation ("discharge rays") from the negative glow.

Fourth type.—Further rarefaction of the air carrying the discharge causes further development of the phenomena at the negative electrode, and shows that the negative glow has become sharply separated from the cathode by a second non-luminous region, called the "Crookes" or "cathode" dark space; the cathode also is enveloped in a velvety film of light, known as the "cathode glow."

When a pressure of about 1/10 000th of an atmosphere is attained these phenomena are found to occupy most of the tube; the positive column has disappeared as such, there being only the thin anode glow over the surface of the anode. With air at this pressure, in a discharge tube 3 cm in diameter and 22 cm in length between electrodes, the Crookes dark space has expanded to about 1·5 cm thickness, and the negative glow, which is fainter and more indefinite, occupies 10 to 12 cm of the length of the tube. The fluorescence of the glass also disappears with weakening of the negative glow.

(*c*) *The generation of cathode rays.*

Exhaustion of the discharge tube beyond the region of the Geissler discharges, i.e. beyond about 1/10 000th or 100 millionths of an atmosphere, causes rapid changes in the discharge phenomena. The anode glow disappears and the cathode dark space expands, driving the remains of the negative glow before it. It is now possible to detect luminous streamers which appear to have a definite direction normal to the surface of the cathode, and penetrate a little way along the length of the tube. Under certain conditions the streamers tend to concentrate into a bundle along the axis of the tube, and their colour shows as a rich purplish blue, quite different from the milky blue of the negative glow. Sometimes also there are scintillations on the surface of the cathode, as though due to bombardment.

As a pressure of 1/100 000th or 10 millionths of an atmosphere is approached, the cathode dark space expands until it fills the tube, and the negative glow disappears, so that the gas as a whole is non-luminous. At this stage the walls of the tube show a bright green fluorescence wherever the dark space reaches the walls. (In the case of soda glass it is an apple-green, quite different from and brighter than the olive-green fluorescence obtained at higher pressures.)

The study of the green fluorescence on the glass was commenced by Plücker † in 1859, and carried on by Hittorf ‡ (1869), Goldstein § (1876) and Wiedemann in Germany, Crookes || (1879) in England, and Puluj in Austria. It was soon ascertained that the fluorescence was produced by something coming from the region of the cathode, for a suitably interposed obstacle cast a sharp shadow on the walls of the tube. Goldstein thought it was a form of ether radiation, and gave it the name "cathode rays." Crookes (1879–85), who studied the velocity of the cathode rays at various stages of the discharge, suggested that the rays consisted of electrified particles of some very attenuated form of matter (a "fourth state"), projected with high velocities by the electric forces near the surface of the cathode. Perrin * in 1895 showed that the charge was negative; and J. J. Thomson † in 1897–98 demonstrated that the particles had a mass of 1/1 850th of

TABLE 5.

VACUUM SCALE

The items are arranged accurately on a logarithmic scale; cases in doubt or covering a range are assigned a mean value	ATMOSPHERES	BARS OR DYNES PER CM²	HEAD OF MERCURY	BOILING POINTS °C. Hg	H₂O
Atmospheric pressure gas-filled lamp, operating	1 ("N.T.P.")	10^6	760 mm	357	100
do. do. cold	0·7				
	0·1	10^5	76 mm	243	45
Steam condenser	0·03				
Neon lamp			10 mm		
Geissler discharges	0·01	10^4	7·6 mm	172	7
Point of max. conductivity (air)	0·003				
	0·001	10^3	1 mm	120	-26
Round's soft valve					
	100 millionths	10^2	0·1 mm	80	
Early carbon-filament lamps	30				
"Western Electric" cathode-ray tube	10 millionths	10	10 microns	43	
Braun's cathode-ray tube	5				
"Gas" x-ray tube	2				
"Lodge" high-tension valve	1 do	1	1 micron	17	
Metal-filament lamp	0·5				
Maximum pressure for "Bright-emitter" valves	0·1 do.	10^{-1}	0·1 do.	-7	
Maximum pressure for "D.E." (thoriated filament) valves	0·01 do.	10^{-2}	10^{-5} mm	-28	
Coolidge x-ray tube	0·003				
	0·001 do.	10^{-3}	10^{-6} mm	-45	
	0·0001	10^{-4}	10^{-7} mm	-58	
Lowest produced & measured (Langmuir, 1916)	0·00001	10^{-5}	10^{-8} mm	-75	

NOTE:- 1 atmosphere ("N.T.P.") = $1{\cdot}013 \times 10^6$ dynes/cm²

* See Bibliography, (39). † *Ibid.*, (40, 41 and 42). ‡ *Ibid.*, (43). § *Ibid.*, (44). || *Ibid.*, (45).

* See Bibliography, (46 and 47). † *Ibid.*, (48).

that of the hydrogen atom, and that their charge was equal to that carried by the hydrogen ion in liquid electrolysis. The particles are now known by the name "electron" suggested by Johnstone Stoney.

(2) THE MECHANISM OF THE DISCHARGE.

The theory of the gaseous discharge * shows that in general the current is carried by both positive and negative carriers. At the low gas pressure in question, the negative carriers are for the most part in the free or electronic condition; it is these electrons which form the cathode rays. The positive carriers, however, are always gaseous ions, i.e. positively charged molecules or atoms of the gas in the tube; these also acquire appreciable velocities and in suitable apparatus may manifest themselves as "positive rays." Owing to their smaller mass, therefore, the mobility of the negative carriers is much greater than that of the positive.

Numerous observers † have investigated the distribution of electric field strength in different parts of the gaseous discharge; and it is found that over the whole range of gas pressures dealt with in the previous sections there is always a high value of electric field in the neighbourhood of the cathode (giving rise to the cathode fall of potential). As a result of this strong field, ions are rapidly removed from the space in front of the cathode (the Crookes dark space); the negative ions, being more mobile, are removed faster than the positive ions, and these latter consequently preponderate and form a powerful positive space-charge. This space-charge, occurring as it does in close proximity to the negatively charged cathode, is sufficient cause for the high values of electric field. The two phenomena are thus interdependent; it is not necessary here, however, to discover which is cause and which is effect.

The negative ions or electrons, moving under the influence of the electric field, accelerate until their energy is sufficient for ionization by collision; the region where this occurs is marked by the negative glow. On an average an electron travels a distance called its "mean free path" before it collides with any gas molecule; therefore the distance between the cathode and the nearest point of the negative glow—in other words, the dimension of the Crookes dark space—is an approximate measure of this mean free path. It is apparent, therefore, why this dark space expands on reduction of the gas pressure.

Similarly the positive ions, supplied from the negative glow, accelerate towards the cathode; but, due to their lesser mobility, it is not until they come right against the cathode surface, where the electric field is greatest, that their kinetic energy is sufficient to produce ionization. In interpreting the results of Ebert ‡ (1900) on the thickness of the Crookes dark space, J. J. Thomson considers that the negative ions are produced mainly in the region of gas lying about ½ mm in front of the cathode (at the higher pressure this region shows the cathode glow). On the other hand, the fact that the cathode fall of potential depends somewhat on the metal employed for the cathode would suggest that electrons may also be emitted by the cathode itself under the action of the rapidly moving positive ions.

* See Bibliography, (49, 50, 51 and 52). † *Ibid.*, (53 54, 55, 56 and 57). ‡ *Ibid.*, (58).

Villard * (1899) clearly demonstrated the action of the positive ions on the cathode. He used a discharge tube fitted with an insulated diaphragm placed parallel to the cathode and fixed between it and the anode. This diaphragm had two holes in it; when the Crookes dark space extended to it (as occurs when the pressure is low enough for cathode-ray production) the only positive ions striking the cathode are the two streams through the two holes; and the points of impact, opposite these holes, are the only parts of the cathode from which cathode rays are emitted. This is conclusive proof that a high value of electric field at the surface of the cathode is not the only condition required for the emission of electrons. Nevertheless, once electrons are available, the electric field at the surface of the cathode, representing as it does the bulk of the potential drop through the discharge tube, is the determining factor in accelerating the electrons, and hence controls the direction and velocity of emission of the cathode rays.

(3) PROPERTIES APPLICABLE TO ELECTRICAL MEASUREMENT.

(a) Properties of the glow discharge.

(i) *The oscilloscope.*—In studying the Geissler discharge in its first stage (see Section III, A, 1—pressure for air about 1/200th atmosphere), H. A. Wilson † (1902) measured the current density at a cylindrical wire cathode when the negative glow does not envelop the whole of the negative electrode. Under these circumstances the glow assumes the shape of a test-tube, with a well-marked lip at the end furthest from the anode; as the current in the discharge increases, the glow reaches further along the electrode, the length of the glow being proportional to the current.

Wehnelt ‡ (1902) has shown that the discharge from the cathode is confined to the area covered by the glow and that the current density is constant over this area. H. A. Wilson demonstrated that these laws hold in air over a pressure range of approximately 1/100th to 1/30 000th atmosphere (the value of the current density being approximately proportional to the pressure).

From this property of the glow discharge we see that it can be used for the direct measurement of electric current; and moreover, being an ionization phenomenon, it shows a quick response to current variations, so that it may be used for oscillographic work. The oscilloscope and the ondoscope illustrate its application.

(ii) *Use of neon.*—We have so far discussed the phenomena of the glow discharge as they occur in rarefied air. The substitution of other gases or gaseous mixtures does not in general alter the character of the discharge. It may affect the values of gas pressure at which the various stages of discharge occur; it will also affect the values of P.D. required across the discharge tube to establish and maintain the discharge.

A notable instance of this is the use of rarefied neon

* See Bibliography, (59). † *Ibid.*, (60). ‡ *Ibid.*, (61).

to carry the discharge; with this gas the minimum P.D. required to maintain a Geissler discharge of the first or second types, for example, averages about one-third to one-half the value necessary with air. This fact is an important factor in the development of the oscilloscope as a practical electrical measuring device.

TABLE 6.

CURRENT DENSITIES AT ELECTRODE SURFACES.

At Cathode (*Negative Electrode*)	Current Density
Glow discharge (cylindrical wire cathode in air): *	amps./cm²
Gas pressure $= \frac{1}{100}$ atmosphere..	0·003
Gas pressure $= \frac{1}{1000}$ atmosphere	0·0003
Glow discharge ("Ondoscope" tubes, made for Prof. MacGregor-Morris by G.E.C. Research Labs., 1923–24):	
Argon	{0·002 / 0·0028
Nitrogen	0·0026
Helium	0·0017
Others	0·0006 to 0·0033
Vacuum arc discharge (mercury-vapour lamp): †	
(at "cathode spot" on mercury surface)	4 000
Arc discharge (carbon arc in air): ‡	
(at "negative crater")	470
At Anode (*Positive Electrode*)	
Arc discharge (plain "Electra" carbons, in air): §	
For 10 mm carbons	44·2
For 6 mm carbons	74·6

(*b*) *Properties of cathode rays.*

(i) *Energy of the rays.*—The fluorescence shown by glass when bombarded by cathode rays, which led to their discovery (by Plücker, 1859), is shown to a very intense degree by certain crystalline minerals, and is now used universally for visual indication of the rays. Bombardment by the rays may also cause chemical and physical changes in matter, as for example the photographic sensitive plate, which is chemically altered by light. As the rays consist of particles of finite mass moving with high velocity, they possess considerable kinetic energy. Wiedemann || (1898) has shown, however, that only a small fraction of this energy is spent in exciting fluorescent radiation. Portions of the energy are converted into X-rays or into secondary cathode rays; but usually the bulk of it is dissipated as heat at the point of impact. (The X-ray tube shows this evolution of heat at its target, which is subjected to bombardment by a concentrated jet of rays.)

...mission *of the rays.*—Goldstein, by suitably-...ow experiments, confirmed Hittorf's observation that the rays travel in straight lines, and showed further that they start at right angles to the surface of the cathode (the rays give no "penumbra" effect as light does). These two properties of perpendicular emission and rectilinear propagation are easily accounted for by the "cathode fall of potential" phenomenon (see Section III, A, 2), and it will be seen that they are essential to the application of the cathode rays to electrical measurement purposes. The effect may be observed directly in the vacuum discharge tube by adjusting the gas pressure to a suitable value (in the neighbourhood of 100 millionths of an atmosphere) such that the trajectory of the rays becomes visible as a pencil of blue light.

(iii) *Deflection of the rays.*—The cathode rays are deflected by a magnetic field having a component perpendicular to their direction of travel, a property first noticed by Plücker * (1859). The direction of the deflection is the same as that of a flexible conductor lying in their path and carrying an "electric current" towards the cathode.

The rays are also deflected by an electrostatic field, as was indicated by the experiments of Goldstein (1876) and Perrin (1895), and finally demonstrated by J. J. Thomson (1897). The difficulty experienced in realizing the electrostatic deflection is due to the very intense ionization produced by the rays in the residual gas through which they pass (as evidenced by the blue streamers of light by which they are first seen). This ionization renders the gas partially conducting, and the resultant effect is as though the rays were moving down a kind of protecting conducting cylinder of their own construction and are thus screened from the action of any electric field applied to the tube, there being, of course, no electrostatic field inside a closed conductor. The effect may be partially eliminated by more complete exhaustion of the discharge tube (to, say, 10 millionths of an atmosphere), thus reducing the amount of residual gas.

(B) USE OF THE ELECTRON JET ("CATHODE-RAY PENCIL") PRODUCED BY GASEOUS DISCHARGE.

(1) REQUIREMENTS.

The property of the cathode rays which renders them useful for measurement purposes is their sensitiveness to deflection by electric and magnetic fields. But the discharge tube that has served so far to show the rays is not suitable as a measuring instrument. It is necessary, for one thing, to separate the rays from the other phenomena of the discharge, so that their response to the deflecting fields may not be affected by disturbing factors. Secondly, and perhaps more important, means must be adopted for measuring the deflection of the rays with more certainty and accuracy.

(2) CROOKES'S APPARATUS.

The first attempt to fulfil such conditions was made by Crookes † (1879) in studying the relative velocities of the cathode rays as the gas pressure was reduced. The apparatus used consisted of a

...aphy, (60). † *Ibid.*, (62). § *Ibid.*, (64 and 65).

* See Bibliography, (41). † *Ibid.*, (45).

vacuum tube with a plane aluminium electrode; parallel to this and $2\frac{1}{2}$ cm in front of it was placed a mica screen with a small hole in the centre. The rays which were projected through the aperture in this screen were received on a glass plate, the small area on which they impinged being marked by a green fluorescence.

(3) Thomson's Apparatus.

For his determinations of the physical constants of the electron, Thomson * (1897) found it necessary to secure a much greater accuracy of measurement. To obtain this he devised the form of discharge tube shown in Fig. 13. A and B are two thick metal discs, which fill the cross-section of the tube and thus separate it into two main portions. Both these metal discs or diaphragms are earthed by the side connection shown. A negative potential is applied to the electrode C, and a discharge is established in the left-hand end of the tube; thus A acts as anode and C as cathode. The electrode C is flat, with its plane perpendicular to the axis of the tube; as a result the

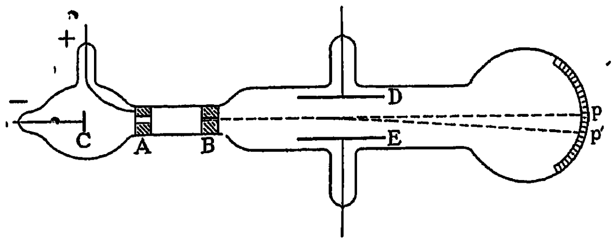


Fig. 13.—Thomson's apparatus for producing an electron jet.

cathode rays generated due to the high exhaustion are projected parallel to the axis, and some of them, instead of being stopped by the anode A, pass through the slit cut in it. These rays that pass through meet B; but the slit in B, though narrower, is parallel to that in A, and therefore a good proportion of the rays will continue in their motion, and form a jet which travels axially along the large right-hand " deflecting chamber " of the tube, eventually bombarding the glass and causing fluorescence thereon at p.

Note first that the discharge is confined to the cathode end of the apparatus, and therefore the rays travelling in the remaining portion of the apparatus are independent of this discharge (except in so far as they are generated by it). Secondly, due to the use of the fine slit in B, the jet of rays which emerges into the deflecting chamber is in the form of a flat strip or thin ribbon; the fluorescence produced on the glass at p therefore takes the form of a short band or line of light, which in its middle portion at least is narrow and sharply defined. It is possible then to make accurate measurements of motions of this line " indicator " in the direction perpendicular to its length.

The electrodes D and E form a condenser for producing an electric field through which the electron jet must pass and which produces a deflection of the jet in the required direction. They are placed inside the apparatus to avoid screening due to conduction on the surfaces

* See Bibliography, (67).

of the glass walls [see Section III, A, 3, (*b*), (iii)]. A deflection may also be produced by means of a magnetic field applied perpendicular to the axis of the tube.

(4) Braun's Apparatus.

The first application of cathode rays to commercial measurements was made by Prof. F. Braun,* also in 1897. This apparatus was much larger than Thomson's and yet simpler in design; it is shown in Fig. 14. K is the cathode, a plane disc perpendicular to the axis of the tube, as before. The anode A, however, is removed to a side tube, so that it is entirely clear of the path of the rays. There is only one diaphragm, C, of metal (aluminium or tin-foil) and it is left insulated; instead of a slit it has a circular hole (about 2 mm diam.). Thus the important result is secured that the jet of rays issuing from the hole and travelling down the tube is cylindrical. Another important modification is the introduction of the " fluorescent screen," a mica plate D coated on the side bombarded by the rays with a fine layer of mineral substance, chosen for its very intense fluorescence under cathode-ray bombardment. This screen then shows a bright round spot of light where the cathode-ray jet falls upon it, and it is possible to measure deflections of it in any direction across the screen; that is, the

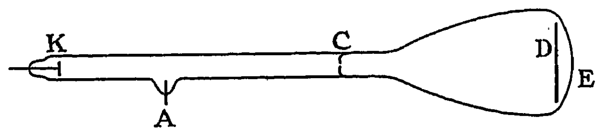


Fig. 14.—Braun's apparatus for producing an electron jet.

instrument gives two-dimensional indications and therefore is a true cyclograph.

(C) Alternative Means of Producing the Electron Jet.

(1) Limitations of the Gaseous Discharge.

Consideration of the theory of the discharge in the cathode-ray tube (see Section III, A, 2) shows that the supply of electrons in a free state, i.e. available for the production of cathode rays, is an integral part of the mechanism of the discharge. Thus with the type of discharge so far discussed there are several severe limitations on the operating conditions. The gas pressure must be reduced to quite a low value (compared with the relatively wide range of values over which the glow discharge phenomena are exhibited). At this pressure the gas has passed far beyond its point of maximum conductance, so that a high P.D. is necessary to produce a satisfactory electron jet in the apparatus; further, the resulting high velocity of the jet renders it comparatively insensitive to deflection, especially by electric fields (see Section XI, B, 3), and so restricts the utility of the instrument in practical engineering. Further, the discharge in the tube carries only a minute current, and in spite of the high velocity this limits the amount of power carried by the jet and hence its ability to produce records with high velocities of traversal.

* See Bibliography, (68 and 69).

It is necessary also that the gas pressure shall remain within certain close limits—a ratio of 1 : 3 is quoted as the average permissible range of variation. This necessitates great care in the construction of cold-cathode instruments (see also Section IV) if they are to maintain satisfactory operation over a reasonable period.

(2) ALTERNATIVE SOURCES OF ELECTRONS.

From these considerations it will be realized that any device which provides a source of free electrons at the cathode of the discharge apparatus will enable some of these limitations to be overcome. There are many of the radioactive substances that emit β rays, which are electrons ejected from the active substance. If, therefore, the cathode surface were covered with a layer of suitable active material, the desired free electrons would be provided, independently of the discharge conditions. The electrons are, however, ejected from the material with velocities usually much higher than those of cathode rays produced by the gas discharge; the problem of harnessing these and directing them down the discharge tube at any desired velocity presents great experimental difficulties. Further, the quantity of electrons obtainable from such a source, bearing in mind the cost in relation to the requirement of a cheap, practical instrument, is certainly too small to permit of selection of the minute fraction that would be passed by a diaphragm such as is used with the cathode rays. Additional complications requiring to be guarded against are the emission of α rays, causing deterioration of the apparatus, and of γ rays, involving danger to the operator of the instrument.

Alternatively, by making the cathode of a suitable metal and subjecting its surface to electromagnetic radiation, electrons may be released from it by virtue of the photo-electric effect. These "photo-electrons" have small velocity and so are available for conversion into cathode rays by an accelerating voltage in the usual manner. Unfortunately, however, the supply of electrons obtainable from a surface of reasonable size is too meagre for practical use.

(3) THERMIONIC EMISSION.

Many experimenters from 1725 onwards have made observations on the electrification produced by hot bodies. Elster and Geitel (1882–89) investigated the effect as produced by incandescent metal wires, and showed that the results were complicated by effects of the gas surrounding the wire, and other causes. Thomson first eliminated these extraneous effects by using a discharge vessel continuously exhausted, and showed that in a high vacuum a metal when first heated emitted a small quantity of positive electricity, but on being raised in temperature it emitted negative electricity at an ever-increasing rate. Edison, Preece (1885) and Fleming (1890, 1896) noted and studied a similar effect with carbon filaments of electric lamps.

J. J. Thomson * (1899) measured the ratio of charge to mass of the negative carriers emitted by an incandescent carbon filament in a high vacuum, and showed that they were of the same nature as the carriers in the cathode rays, i.e. free electrons.

* See Bibliography, (70).

Wehnelt * (1904) found that the emission of negative electricity from certain salts, notably oxides of the alkaline earth metals, was of much greater magnitude than had been noted with other substances.

(4) INTRODUCTION OF THE HOT CATHODE.

(*a*) *Effect on the discharge.*

It has been shown (see Section III, A, 2) that in the gas discharge the region of gas in the neighbourhood of the cathode is rich in positive ions but poor in negative ions, this being the condition that gives rise to the cathode fall of potential.

Schmidt † (1903) showed experimentally that if by any convenient method negative ions are introduced into this region, so preventing this impoverishment, then their presence results in a lowering of the potential drop at the cathode.

Wehnelt ‡ (1904) used calcium oxide or barium oxide mounted on a strip of platinum foil arranged to be heated by an electric current; this device, sealed into a discharge tube and connected as cathode, served as a plentiful source of negative ions when heated, due to the thermionic emission described in the previous section. With this "hot cathode" the potential drop at the cathode may be reduced to a few volts, whereas its value with a "cold cathode," when penetrating cathode rays are being produced, is many kilovolts. Thus with the anode placed close to the cathode (to eliminate the positive column) a current could be sent through the discharge tube with a P.D. of little over 20 volts.

Wehnelt § further showed that by increasing the P.D. applied to his discharge tube, and at the same time limiting the thermionic emission of his cathode (by control of its temperature), the rate of disappearance of negative ions caused by the passage of the current could be made to exceed the rate of emission; by this means a potential-drop could be re-established at the cathode, of any desired value, depending upon the amount of surplus P.D. applied to the tube. By this means, therefore, it was possible to produce cathode rays of any desired velocity (since their velocity is dependent on the electric field that accelerates them, and therefore on the cathode fall of potential).

It is important to note that the function of the hot cathode applied to the discharge as above described is really of the nature of a stimulant to a mechanism already existent; for although the hot cathode certainly introduces electrons by virtue of its own thermionic emission, the discharge is still being carried largely by gaseous ions. The increase in the current carried in the discharge is due not so much to the electrons liberated and accelerated by the applied P.D. as to the extra ionization that these produce. In fact, there is always a strong tendency for a discharge of this type to develop into an arc discharge. In this connection Wehnelt states that it is not advisable to use a P.D. higher than 1 000 volts in his apparatus (see also the next Section) as otherwise the intense positive-ion bombardment causes cathode rays to come off from that part of the

* See Bibliography, (71). † *Ibid.*, (72). ‡ *Ibid.*, (71). § *Ibid.*, (73).

platinum strip that is bare, resulting in bad disintegration.

(b) *Wehnelt's apparatus.*

In 1905 Wehnelt* designed an electron-jet instrument incorporating the hot-cathode device previously described; this is shown in Fig. 15. K is an edge view of the platinum strip, stretched between two supporting wires; A is a metal diaphragm which serves also as anode; S is a screen coated with fluorescent material, as used in Braun's apparatus. C_1 and C_2 are two condenser plates for electrostatic deflection of the jet, as used by J. J. Thomson. The strip K carries on its side facing the anode a spot of lime, about the size of a pin's head; and when a P.D. of a few hundred volts is applied between the hot cathode and the anode an intense stream of cathode rays is emitted from the lime spot, their path being marked by a bright blue line showing ionization of the residual gas.

Since the width of the strip of platinum is greater than the diameter of the electron source, i.e. the lime spot, the intense field at the cathode surface will not depart much from perpendicularity to the surface; this is the more true, the higher the cathode fall of potential that is used. As a result, then, the rays are given the

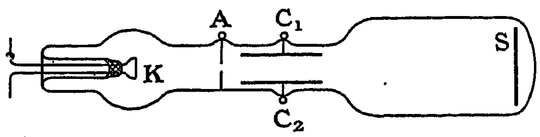


FIG. 15.—Wehnelt's apparatus for producing an electron jet.

bulk of their momentum perpendicular to the cathode surface, and so tend to form a parallel beam of diameter corresponding to that of the lime-spot source.

Thus, limiting the size of the lime-spot source contributes dually to the fineness and intensity of the cathode-ray stream produced by the apparatus, independently of the use of a diaphragm—first by limiting the initial diameter of the stream, and secondly by ensuring that the effective part of the accelerating field shall be more nearly parallel.

With the gas pressure in such a discharge tube reduced to a sufficiently low value, in the neighbourhood of 10 millionths of an atmosphere, as for the cold-cathode discharge, the absorption of the rays by the residual gas is decreased, and a fine pencil of them passes through the aperture in the electrode A, forming the "electron jet."

(5) NEW PROPERTIES OF THE ELECTRON JET.

Wehnelt (1905) first demonstrated the enormous increase in sensitivity that could be obtained from a jet instrument when fitted with his hot lime-spot cathode, and run on a lower P.D., and showed that it was due to the lower velocity of the cathode rays as compared with those of the Braun tube previously used (see also Appendix). This increased sensitivity of the electron-jet instrument greatly enhances its utility for all manner of investigations. An additional advantage is the lower P.D. used on the instrument—it becomes possible to run it from public mains, or even from batteries—so that the complete apparatus may be made portable if desired; for a small accumulator suffices to supply heating current for the cathode strip. The independent source of electrons also enables the current carried by the discharge, and hence the intensity of the electron jet produced, to be increased at will independently of the P.D. used, thus increasing the power available in the jet for registration purposes.

There are disadvantages, however, in the use of a low jet velocity, primarily because of the "absorption" of the rays by the residual gas in the apparatus. Glasson (1911) found that the ionization produced by an electron per unit distance travelled was inversely proportional to the square of its velocity—thus by decreasing the velocity of the jet in the ratio of 10 : 1, as is possible in changing from a cold-cathode to a hot-cathode instrument, the ionization per unit distance is increased in the ratio 1 : 100. However, not all of the collisions of the electrons with molecules are productive of ionization, so that the disparity between the absorptions of slow and fast rays will not be so great. The effect may be observed even in the cold-cathode tube with a higher gas pressure [see Section III, A, 1, (c)]—the cathode rays, so long as their speed remains high, pursue an even course; as they slow down they become more and more liable to deflection by the encountered molecules, until finally they lose so much energy as to be indistinguishable as cathode rays.

There is a further cause contributing to the "loss of entity" of an electron jet, and that is the divergence or scattering of the jet due to the mutual repulsion of the like-charged electrons. It is shown in the Appendix that the rate of increase of diameter of the jet is a function of time, and that a slow jet shows a larger scattering than a fast one, due to its longer time of transit from source to screen.

(D) THE PURE ELECTRONIC DISCHARGE.

(1) ELIMINATION OF THE POSITIVE ION.

The values of thermionic currents from heated substances obtained by different observers had varied between wide limits. Moreover, the substances usually worked with (platinum and carbon) are so difficult to free completely from absorbed gas that it was thought the emission phenomenon might be closely bound up with the presence of gas in the metal—as indeed it is in the case of positive ion bombardment. It seemed, therefore, that with the cleaner conditions, i.e. greater freedom from gas, that could be realized with the use of tungsten, the thermionic currents might cease altogether. In fact H. A. Wilson (1903) stated the probability that a pure platinum wire heated in a perfect vacuum would not discharge any measurable quantity of electricity, either positive or negative. The experiments of Langmuir, however, were reassuring—he found that after a certain high degree of exhaustion had been reached, the thermionic currents increased up to a certain limiting value as the tube became freer and freer from gas.

Coolidge (1913) when working even with tungsten electrodes in a tube designed so that the electrodes could be heated in situ to very high temperatures,

* See Bibliography, (74).

found that the positive ion effect would persist for hours, disappearing completely, however, as the electrodes became sufficiently freed from gas. He pointed out also that although the idea of using a hot cathode was not new (e.g. Wehnelt's experiments, see previous Section) the principle had not previously been applied successfully in such a high vacuum that the positive ions did not play an essential rôle. Thus in his hot-cathode X-ray tube Coolidge * used a filament of tungsten wire as cathode, which with a temperature range of 1 890° to 2 540° K. produced a sufficiently copious supply of electrons (up to 40 mA could be passed through the tube), the amount being dependent only on the temperature of the filament, and independent of the vacuum conditions. In other words, gaseous conduction played no part in the discharge, the current being carried wholly by the electrons liberated at the cathode. To secure this result great care was necessary in the exhaustion of the tube—the heating to incandescence of the electrode in situ, and the baking of the glass envelope while being exhausted; the pressure reached did not exceed a few hundred millionths (1×10^{-8}) of an atmosphere.

(2) ADVANTAGES OF ELECTRONIC DISCHARGE.

One of the main advantages of securing satisfactory operation of an electron-jet instrument with a purely electronic discharge is that since the residual gas is no longer required to play any part in the discharge it may be removed as completely as manufacturing technique will allow. Thus one of the chief obstacles to the successful use of low-velocity jets, viz. the absorption of the "rays" by the residual gas, is removed. Practically, however, there are other factors of even greater importance. The Wehnelt type of cathode is not a satisfactory device for use in a commercial instrument—it shows "fatigue" effects, and it emits gas, so that it is not possible with it to reach the high vacuum necessary for a pure electronic discharge. These disadvantages are doubtless due largely to the positive ion bombardment that necessarily accompanies the gaseous discharge.

PART 2.

DEVELOPMENT OF THE ELECTRON-JET INSTRUMENT.

(IV) THE COLD-CATHODE INSTRUMENT.

The apparatus described by Braun † (1897), which has been described (Section III, B, 3), was used by him first as an oscillograph with one-dimensional deflection of the indicating spot of light viewed through a rotating mirror. Subsequently he used the instrument as a cyclograph for investigating phase relations with polarized electrolytic cells. With this method he obtained stationary curves on the fluorescent screen (as explained in Section I). Electromagnetic deflection of the jet was used. Braun says little about experimental difficulties in the use of this new apparatus, the satisfactory construction of the tubes being left in the hands of the makers, Herr Franz Müller, of Bonn.

Two years later Zenneck * sent to the same manufacturer for cathode-ray instruments, and as a result of his use of them made certain improvements in the design. He used two separate diaphragms in place of one, and used a metal plate with a hole in it, like a diaphragm, as the anode instead of the small electrode

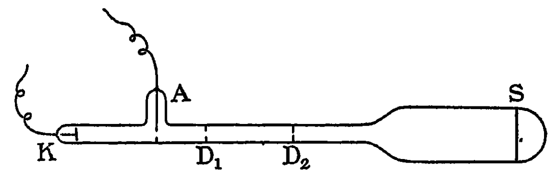


FIG. 16.—Zenneck's tube.

in a side tube. Thus in effect the rays are "stopped-down" three times instead of once (see Figs. 16 and 17).

The tube was used as an oscillograph with a uniform time deflection applied to the electron jet; the resulting wave curves were recorded by photography with an ordinary camera. The exposure required was of the order of 10 mins., and in order to shorten this time Zenneck tried to get a brighter spot on his screen by faster running of the electrostatic machine that supplied the tube. This led to a troublesome unsteadiness of the discharge and flickering of the ray. This was

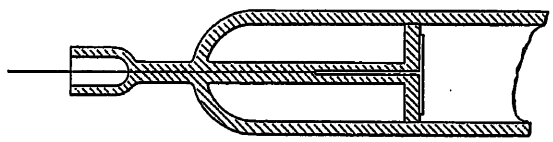


FIG. 17.—Zenneck's cathode.

largely remedied by the use of an insulating backing to the cathode as shown.

Milham † in 1901 used a tube made by Müller-Uri to Zenneck's design for measuring electric fields (between external deflecting plates), but trouble was experienced with obtaining a steady electrostatic deflection of the jet "due to ionization of the residual gas."

In 1902 one of the present authors ‡ designed a

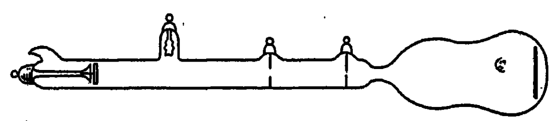


FIG. 18.—Cossor tube.

modification of Prof. Braun's apparatus, and demonstrated its use for the determination of the maximum value of an alternating current. This tube incorporated Zenneck's improvements, including a cathode with a glass shield, and was smaller and therefore more compact than the original tube; it was manufactured by Cossor (see Fig. 18).

In 1903 Ryan § reported his work on wave-forms using the cathode-ray tube on the cyclographic method.

* See Bibliography, (75 and 76). † *Ibid.*, (68 and 69).

* See Bibliography, (77). † *Ibid.*, (78). ‡ *Ibid.*, (1). § *Ibid.*, (79).

He had "found that the tubes on the market were altogether too small to be of practical use." He required the fluorescent screen of double the size (i.e. 6 in.) and in 1900 after many trials Müller-Uri of Braunschweig succeeded in delivering two tubes with screens .5 in. diam. (see Fig. 19). These large tubes proved unsatisfactory at the outset, giving an intermittent cathode-ray jet; this trouble was traced to corona and external leakage of the high-tension supply, and was overcome by a thick jacket of solid insulation (ebonite discs sealed on with paraffin wax, surrounding the cathode end of the tube). The trouble would probably have been avoided by making the tubes with an extended glass neck at each electrode, as is the practice with X-ray tubes.

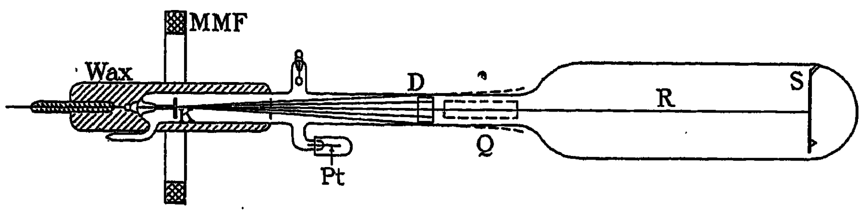


FIG. 19.—Müller-Uri tube used by Ryan.

Rankin * in 1905 used a Müller-Uri tube similar to that used by Ryan. The tube was fitted with an osmosis vacuum regulator, to enable the vacuum to be softened and so avoid the use of too high a P.D. on the tube which results in flickering of the jet. The tube was worked with a P.D. of from 17½ to 20 kV. Rankin also investigated the effects of using a "concentrating coil" with the tube.

In 1911 Ryan † reported further use of the large Müller-Uri tube, operating on an excitation of 10 kV. Successful use was made of external condenser plates for producing electrostatic deflection of the electron jet for both components, the apparatus being used as a cyclograph. This is the first use of the electron-jet instrument for measuring power losses in high-tension circuits.

Roschansky ‡ in 1911 experienced a flickering of the jet in the cold-cathode tube when driven with a high P.D. He was studying the oscillatory spark discharges of a condenser, and since these involved high-frequency variables it was essential to have a steady jet. Roschansky traced the trouble to the region of the exhausted tube behind the cathode disc, as Zenneck had done, and filled this space with crumpled tin-foil held in place by a metal screen (as shown in Fig. 21). He also introduced the tubular type of anode (serving also as diaphragm, like Zenneck's arrangement).

Roschansky used in his tube, for the first time since J. J. Thomson's experiments, electrostatic deflecting plates mounted inside the vacuum; these were shielded at each end with diaphragms having holes large enough to allow passage of the deflected jet. The axial focusing coil was also used (see Fig. 20).

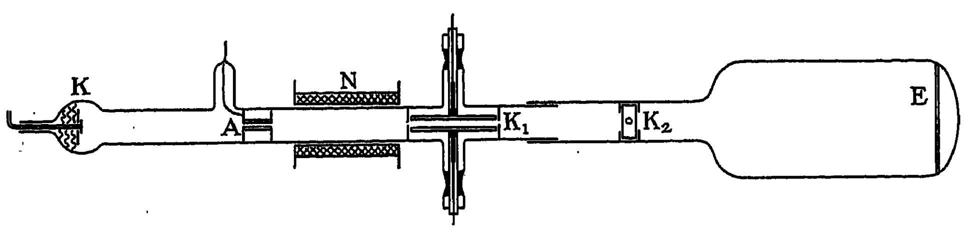


FIG. 20.—Roschansky's tube

For his work on the spark excitation of "undamped" waves Chaffee * (1911) imported Müller-Uri tubes from Germany. These, however, he altered, inserting a ring anode and substituting a glass diaphragm in the form of a truncated cone, having a hole about ½ mm diam. Condenser plates for electrostatic deflection were also mounted inside the tube. The tube was kept connected to a pump, and the best condition of vacuum was that which gave a ray bundle about 1 mm in diameter at the cathode. Excitation was at 29 kV.

Minton † (1915) found that the tubes on the market that had been developed and used by previous investigators (see Fig. 22) were not satisfactory for his purpose,

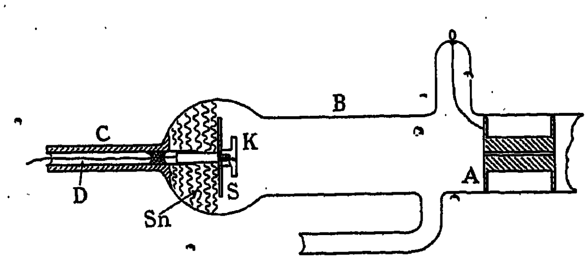


FIG. 21.—Roschansky's cathode and anode.

which was to develop a method of testing that was suitable for commercial routine, together with appropriate apparatus that would be sufficiently constant and dependable, "ready for use at any time, just like a galvanometer is." In this connection steadiness of

* See Bibliography (80 and 81). † *Ibid.*, (82). ‡ *Ibid.*, (83).

* See Bibliography, (84). † *Ibid.* (85 and 86).

vacuum conditions is one of the essential factors. Some workers had obtained this by prolonged baking of the tube while on the exhausting pump, but tubes so treated showed the flickering of the jet to a greater extent than before.

Ryan (1908) had found external discharges and eliminated them by a jacket of solid insulation, and Rankin (1905) had used a tube with an osmosis regulator which eliminated the necessity for using an excessive exciting P.D. However, Zenneck (1899) had discovered that discharges took place inside his tube, apparently between the cathode and the glass. To avoid this the cathode was set in a close-fitting glass sheath; but Minton found the trouble still present with this arrangement. Again, Roschansky in 1911 had tried to eliminate the trouble with tin-foil leaves that would conduct away the charges.

Minton found that his early tubes, which, due to lack of careful exhaustion, tended to soften (in vacuum) with use, were free from this defect. Evidently the film of adsorbed gas which remained on the glass surface of such tubes constituted a sufficient leak for the charges that accumulated. It was then found possible by means of a proper adjustment of the heat treatment given to the tubes during exhaustion (i.e. ½ hour at 350° C.) to effect a satisfactory compromise, "thus attaining steadiness of vacuum for several hours' continuous heavy operation, while leaving on the glass sufficient gas film to conduct away the charges."

In 1914 Dufour * proposed using the electron-jet instrument for recording extremely rapid transient phenomena, and pointed out the necessity of developing an instrument sufficiently powerful to produce the required permanent trace with a single transit of the jet across the recording plate, and showed how high the velocity of this transit may be expected to be (up to 3 km per sec.).

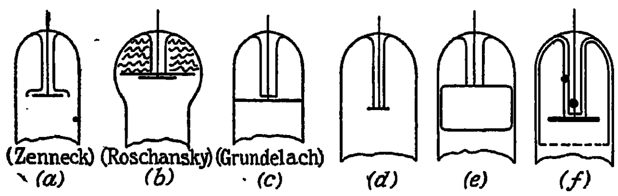


FIG. 22.—Comparison of cathodes (after Minton).

In 1918 Dufour described his first apparatus designed to carry out this idea (see Fig. 23). In his discharge tube for producing the electron jet there was no radical departure from the practice of his predecessors. However, liberal length was allowed, for the glass stem supporting the cathode, for the discharge volume (between cathode and anode), and for the anode itself, which was tubular and carried a diaphragm at each end.

The apparatus was kept connected to the vacuum pump, and the gas pressure correctly adjusted—on the one hand to take advantage of the high P.D. to secure a fine and intense trace, and on the other hand to prevent the occurrence of discontinuity of the discharge (giving a flickering jet) and brush discharges on the external conductors.

* See Bibliography, (87, 88 and 89).

In 1922 Dufour described an attempt at a "double" instrument. In this apparatus there are two similar discharge tubes, each complete with anode-diaphragm, mounted in inclined positions on the two branches of a Y-tube (see Fig. 24). The two electron jets produced are first separately acted upon by their respective deflecting fields, then, further on in their paths, when they have approached each other fairly closely, they are turned into parallel directions by small electromagnets. The two discharge tubes are found to function simultaneously when a liquid resistance is connected in series with each cathode. Experience shows, however, that the operating conditions will never be identical in the two discharge tubes, and the resulting inequality of the sensitivity of the two rays renders it impracticable to use a double instrument for high-frequency work, in which the jets must respond to a number of auxiliary deflecting fields.

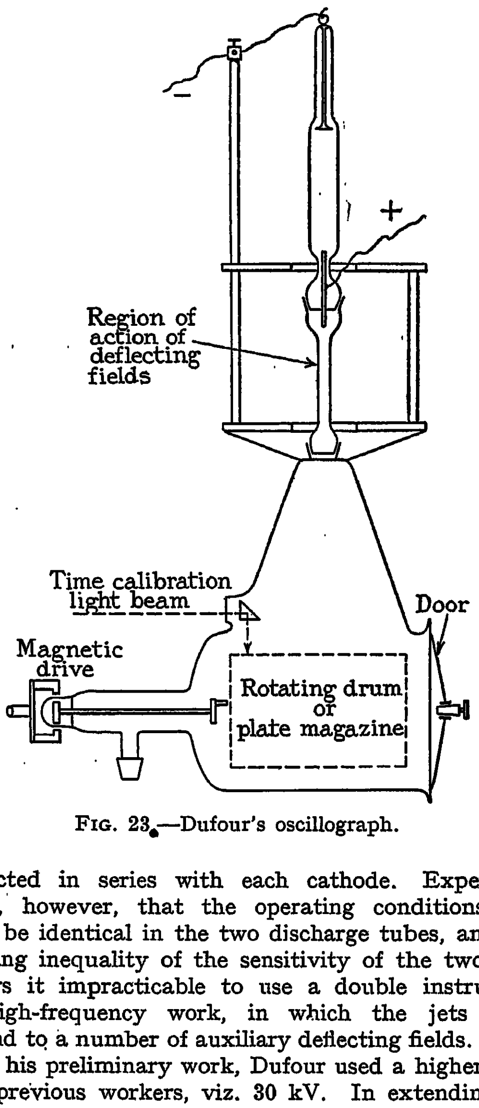


FIG. 23.—Dufour's oscillograph.

For his preliminary work, Dufour used a higher P.D. than previous workers, viz. 30 kV. In extending the frequency range of his oscillograph, however, it was necessary to increase this up to 60 kV, giving an increased intensity of jet that would compensate for the higher velocity of traversal across the photographic plate. However, at the highest frequencies tried a definite limit was found—not because of insufficient power in the jet to give a readable record with the high velocity of traversal, but because of too great an

intensity. For with the cold-cathode discharge the current carried by the jet increases faster than its velocity, hence with increased power on the tube the electron density increases, and this gives rise to increased "scattering" of the jet (see Appendix B, 5), and a point is reached where the blurring and faintness of the trace due to this cause more than counterbalances the gain due to the increased velocity of and current in the jet.

Hull * (1921) concluded that the flickering troubles associated with charging of the internal surface of the glass were due to the influence machine largely used by previous investigators for exciting the cold-cathode instrument, and found that the difficulty was reduced to a minimum by using a steady source of high-tension power, such that earthing the anode and also an electrostatic shield surrounding the tube in the neighbourhood of the screen were sufficient to stabilize the conditions of discharge and electron flow down the tube. The high-tension supply was derived from a step-up transformer running on alternating current and two Kenotron (diode) rectifiers, and was taken through a smoothing circuit (consisting of two 0·04 μF condensers and a 5H inductance, with the π-connection). The arrangement was thus little different from Minton's, who used a mechanical (rotary commutator) rectifier, and a plain stabilizing resistance instead of a smoothing circuit.

Hull used a polished concave cathode having a radius of curvature somewhat less than the distance to the screen (see Section VI, C, 2), and a diaphragm with a very fine hole 0·01 in. diam. (see Fig. 25). The diaphragm was made in two parts, with a shielded opening round the outer edge to allow free passage of gas during exhaustion. The tube was baked at 350° to 400° C. in an electric furnace while connected to the pump, the optimum point being reached with the dark space extending 0·2 to 1·2 in. from the cathode, corresponding to a gas pressure of from 4 to 13 millionths of an atmosphere. With an applied P.D. of 10 kV the current was 50 to 500 μA.

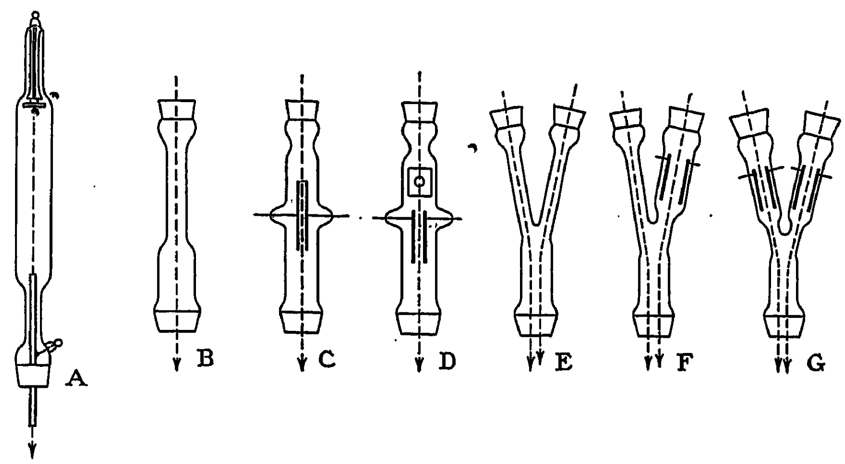


FIG. 24.—Dufour's discharge tubes.

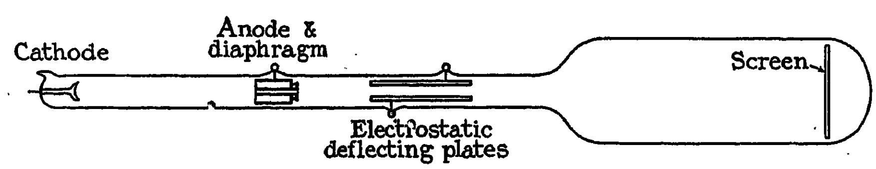


FIG. 25.—Hull's cold-cathode tube.

(V) THE HOT-CATHODE INSTRUMENT.

(A) WITH "LIME-SPOT" CATHODE.

The first electron-jet apparatus to incorporate a "hot cathode" (i.e. using thermionic emission to stimulate the discharge) was that of Wehnelt * (1905); this has already been described [Section III, C, 4, (b)]. The outstanding advantages gained by the use of this apparatus are the production of a very intense electron jet (due to the heavy electron emission from the hot lime) combined with a much greater sensitivity to deflection (due to the low jet velocity).

About 1909 A. G. Warren, F. Murphy and one of the authors worked in the same direction. A standard Braun-Wehnelt apparatus was first tried, but had soon to be abandoned as it proved incapable of giving consistent results. The chief experimental difficulty encountered was "clean up" or hardening of the vacuum (reduction of gas pressure) taking place simultaneously with the discharge. As a result of this the cathode emission diminished, thus further emphasizing the loss of positive ionization, so that

* See Bibliography, (90).

* See Bibliography, (74).

the instrument rapidly became unworkable. It was found that if any reasonable constancy of emission was to be obtained, it was necessary to keep the gas pressure constant and as low as possible, obtaining the necessary emission by coating the cathode. Further than this, the emission was found to be determined chiefly by the physical condition of the electrodes rather than the controllable variables mentioned above. In fact it has been more recently established by Ratner * that the gas which functions in these phenomena is not so much the free gas in the apparatus as the adsorbed gas and the absorbed gas.

Subsequently a new apparatus was built, designed to be kept connected to the vacuum pump (see Fig. 26). It was found necessary to make the cathode adjustable, so that the platinum strip carrying the lime spot could be tilted both horizontally and vertically. Dr. Willows kindly assisted these investigators in the technique of producing the lime-spot cathode. Also the fluorescent layer was carried on the inner surface of a cover plate which closed the large bulb of the apparatus (with a ground joint). It was thus possible to renew the active material when it became fatigued. A reasonable "spot" was obtained which did not break up on deflection. Unfortunately at this promising stage the work had to be left.

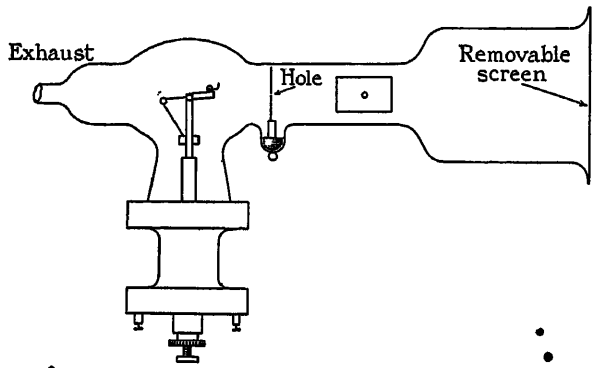


FIG. 26.—Apparatus of Morris, Warren, and Murphy.

Willows and Picton † (1910) investigated the Wehnelt type of cathode, its behaviour under different conditions of operation, and its alteration with time. Lime heated on platinum foil showed not fatigue but on the contrary a considerable increase in activity, up to ninefold with P.D.'s greater than the saturation value, and up to twofold with lower P.D.'s. When heated on nickel foil the lime showed an increase in activity to a maximum, followed by a decrease, with the higher P.D.'s; with the lower P.D.'s its behaviour was similar to that with platinum. No connection could be determined between the activity and the quantity of electricity passed. On first starting a discharge great irregularity was shown; other causes than temperature, such as mechanical vibration, greatly influenced the emission of ions.

The lime coatings used in these experiments were examined under the microscope, and were found to be very adherent to the platinum—in fact it was impossible to free the platinum again from the activity with which the lime endowed it. This effect was attributed to diffusion of the lime into the platinum.

Knipp and Welo * (1915) used an electron jet instrument (see Fig. 27) as a magnetometer for measuring the earth's field. To obtain the necessary sensitivity a hot cathode of the Wehnelt type was used. Records were obtained by direct registration of the jet on a photographic plate mounted in the vacuum chamber (see Section VII, B); and although the photographs show the width of the spot to average about 10 per cent of the deflection, an accuracy of measurement to within 0·3 per cent was claimed on an average of seven readings.

An additional reason for the use of a lime-spot cathode for this work was the necessity for obtaining a definite jet of sufficient range without the use of diaphragms (since the whole instrument is immersed in the "deflecting field"); this was found possible when the spot of lime (ignited sealing wax) did not exceed 0·02 cm (8 mils) in diameter. The cathode was mounted on a double ground joint (see Fig. 28) permitting adjustment (tilting) in two directions—the two adjustments were found necessary for producing a well-defined indicator; this was usually a drawn-out band 2 or 3 cm in length (in the plane of the platinum strip). In passing between the two electrostatic deflecting plates mounted in the apparatus the stream of electrons was not narrow, but spread out, and only a bluish glow was visible. Beyond the plates, however, two converging streams could be seen, these generally crossing at the further end of the tube. The position of crossing depended on the heating current supplied to the cathode, frequently more than one value being found which would give a satisfactory result; the lower temperature was usually chosen.

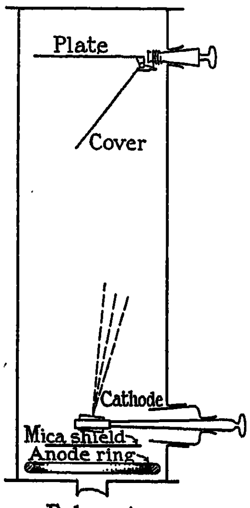


FIG. 27.—Apparatus of Knipp and Welo (general arrangement).

The above-described behaviour of the discharge indicates strongly the presence of an "ionic focusing effect," similar in principle to that developed by

* See Bibliography, (91). † Ibid., (92).

* See Bibliography, (93 and 94).

Johnson (see Section VI, C, 2). The exhaustion of the tube was assisted with a charcoal trap immersed in liquid air. The gas pressure actually used in making measurements is not given, but the statement is made that the Wehnelt cathode ceases to act if the pressure is less than about one millionth of an atmosphere. It

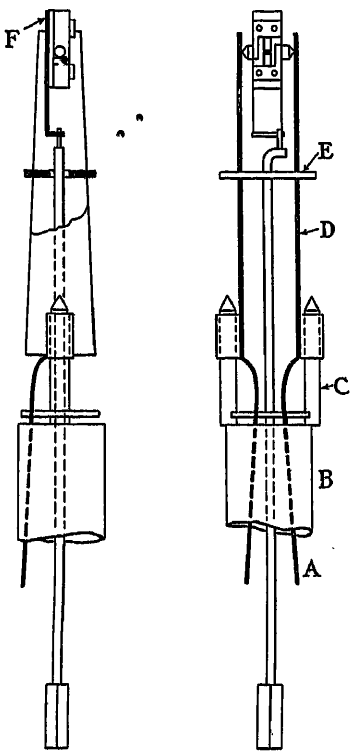


FIG. 28.—Adjustable lime-spot cathode used by Knipp and Welo.

was found best to renew the lime for each exposure, and, owing to the difficulty of mounting a new spot of such small size immediately over the old one, the platinum strip had to be renewed also. In both the preliminary and the final forms of the apparatus the anode was mounted behind the cathode, and the successful working obtained with this arrangement demonstrated clearly the important part played by the fall of potential at the cathode in accelerating the electrons. The total P.D. applied to the apparatus was from 800 to 1 000 volts.

Crooker * (1918) constructed an instrument on lines similar to the foregoing (see Fig. 29). The cathode was a gimbal-mounted platinum strip carrying a lime spot; the lime used for this was mixed with a little barium nitrate to facilitate application as a paste, and to ensure a longer life. The anode was annular in form and mounted quite close (about 1 cm) in front of the cathode; in addition it was found necessary to use a diaphragm (which was placed beyond the magnetic deflecting field) to cut off extraneous light from the hot cathode strip, and also to stop down the divergent jet. The P.D. used to operate the instrument was 300 to 400 volts, and it was found advisable to have the fluorescent screen as close to the cathode as was consistent with the sensitivity required of the apparatus.

It was necessary to maintain a very low gas pressure, exhaustion being assisted with charcoal in liquid air. The hot lime cathode gives off gases quite freely, necessitating constant pumping if the instrument is to be used for any length of time.

(B) WITH BARE TUNGSTEN FILAMENT.

Coolidge * (1913) demonstrated the practicability of using a pure electronic discharge, producing, in fact, cathode rays in his hot-cathode X-ray tube. The hot cathode (see Fig. 30) was an electrically heated filament, made from tungsten wire 0·216 mm diam., closely wound into a flat spiral and mounted inside a coaxial focusing hood (see Section VI, D, 3) whose bore was 6·3 mm. With an input of 23 watts for heating, the temperature attained was 2 540° absolute, and the emission current (constituting also the discharge current) was 40 mA.

Samson † (1918) applied the principle to the electron-jet instrument. His hot filament was made also of tungsten wire (0·2 mm diam.), wound spirally and mounted in a hood, and the maximum emission current obtained was about 10 mA. The first instrument constructed (see Fig. 31) was kept connected to the vacuum pump, and exhaustion was continued until an 8-inch spark coil failed to pass a discharge (with the cathode cold). The instrument was equipped with an aluminium diaphragm 2 mm thick and having a 1-mm diam. hole; this served also as anode. The accelerating P.D. used varied from 1·5 to 9 kV, and an axial coil was used to help to "focus" the jet.

The second instrument built (see Figs. 32 and 33) was sealed off and hence portable; exhaustion lasted for 10 hours, during which time the whole apparatus was baked at 365° C., the filament also being kept glowing. When

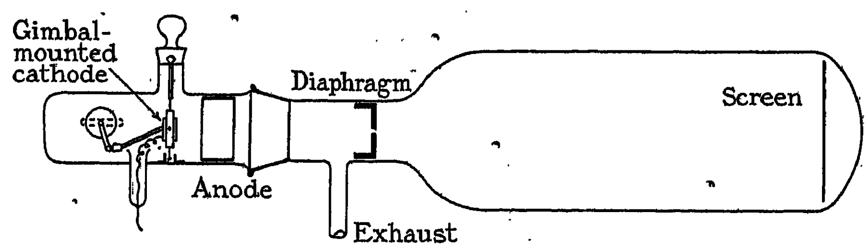


FIG. 29.—Apparatus of Crooker.

* See Bibliography, (95).

* See Bibliography, (75 and 76). † Ibid., (96).

working subsequently the path of the electron jet was absolutely invisible, demonstrating the absence of ionization. In this instrument the diaphragm was placed nearer to the anode (5 cm distant) and was made of nickel on account of its higher melting point. Two condenser plates for electrostatic deflection of the jet were mounted inside the apparatus; two diaphragms

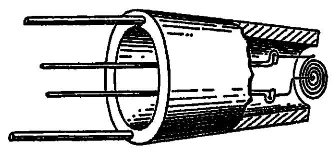


FIG. 30.—Coolidge's hot cathode.

were placed one at each end of these plates, with holes 8 and 10 mm diam. respectively, in order to prevent the emission of "secondary electrons." In this case also a focusing coil (of 500 ampere-turns) was used, placed in the plane of the anode; the fluorescent screen showed a bright blue spot 5 mm diam.

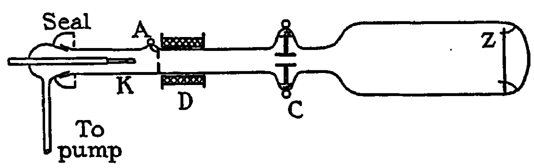


FIG. 31.—Samson's first tube.

Lübcke * (1918) also used a bare tungsten filament, but it was wound into a helix, instead of a flat spiral; it was mounted with its axis perpendicular to that of the tube, and no focusing hood was fitted. A single diaphragm, about 15 cm distant from the filament, served also as anode. Different jet velocities were

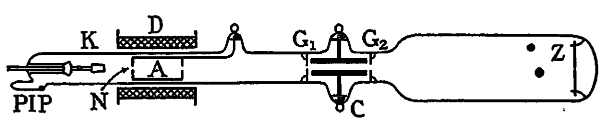


FIG. 32.—Samson's portable tube.

used, the accelerating P.D. covering a range of from 220 to 23 000 volts.

Keys † (1921) also used a hot cathode of the Coolidge type. The other important features of his instrument (see Fig. 34) were a fine axial tube in place of a fine

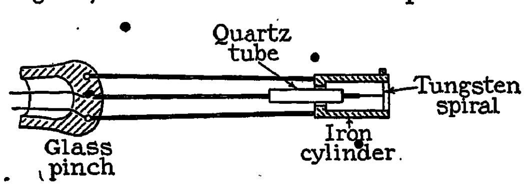


FIG. 33.—Samson's hot cathode.

hole in the diaphragm-anode, and a guard tube extending round the electrostatic deflecting plates and beyond to the metal chamber housing the photographic plate (in the vacuum). This chamber and the guard tube were connected to the anode and earthed. Focusing of the spot was secured by adjustment of the accelerating P.D. (normal value 5 kV), and by axial rotation of the cathode, which was mounted on a ground stopper for the purpose.

Wood * (1923) built an instrument on the same lines as that used by Keys. After trying different arrangements of filament, hood and anode with a view to solving the focusing problem (see also Section VI), the Coolidge type of cathode and the fine tubular anode were adopted. A plain tungsten filament was first used, but a filament of the coated type was preferred.

Wood developed his instruments into a robust form,

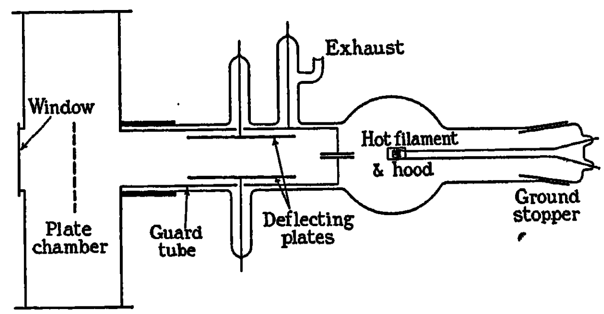


FIG. 34.—Keys's oscillograph.

suitable for use in workshop rather than laboratory. It was built of metal except for a glass drying bulb and the glass mounting to insulate the cathode; it was arranged so that it could be dismantled in a minimum of time, by means of ground joints. Permanent connection to the vacuum pump was necessary, since records were made on a photographic plate placed inside the vacuum.

(C) WITH COATED FILAMENT.

For his first hot-cathode instrument (see Fig. [35), Hull † (1921) made use of the screen and bulb of the Müller-Uri cold-cathode instrument. The anode was in

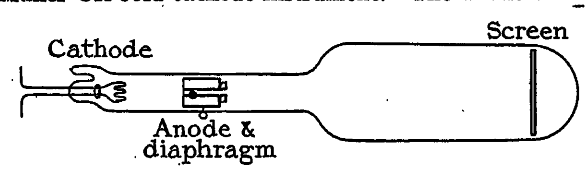


FIG. 35.—Hull's hot-cathode tube.

the form of a ring, fitting the glass tube closely, and the cathode, a platinum strip 1 mm wide carrying a deposit of Wehnelt oxides "the size of a pin's head" was fixed in position. No filtering diaphragm was used, the idea being to rely upon a powerful focusing coil of 500 ampere-turns and the limited size of the emitting surface for obtaining a fine spot [see also Knipp and Welo (1916), and Crooker (1918), Section V, A].

In later instruments, however, a diaphragm was used, with a 0·01-in. hole, similar to that used in his cold-cathode instruments (Section IV). With an accelerating P.D. of 500 volts, the spot obtained was

* See Bibliography (14). † Ibid., (97 and 98

* See Bibliography, (99). † Ibid., (90).

TABLE 7.*

Properties of Electron-Jet Instruments.

Cold Cathodes.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Ref. No.	Authority	Date	Details of instrument													Discharge			Measured sensitivity	
			Maker	Overall length	Distance, cathode to anode	Distance, diaphragm to screen	Cathode		Anode		Diaphragm		Screen			Vacuum, millionths of an atmosphere	P.D.	Current	Electric, cm per volt	Magnetic, cm per gauss
							Form	Diam.	Type	Diam.	Size of hole	Diam.	Form	Diam.	Fluorescent material					
				in.	in.	in.		in.		in.	in.	in.		in.			kV	mA		
68	Braun, F. ..	1897	Müller-Uri	16	4	7½	Flat	—	Side	—	0·08	1½	Flat	3⅛	—	—	—	—	—	—
1	Morris, J. T. ..	1902	Cossor	20½	3	8¼	Flat	⅝	Side	—	0·031	¾	Flat	3	Willemite	—	10	0·01	(0·006)	—
79	Ryan, H. J. ..	1903	Müller-Uri	29½	6½	13½	Flat	—	Side	—	—	—	Flat	5	—	—	10	—	—	—
81	Rankin, R... ..	1905	Müller-Uri	34	6	—	Flat	—	Side	—	—	—	Flat	4¾	—	—	20	—	(0·013)	—
85	Minton, J. P. ..	1915	(Own)	30	—	—	Flat	—	Side	—	0·031	—	Flat	4½	Willemite	5 to 10	20	—	—	0·003
89	Dufour, A.	1920	(Own)	—	—	—	Flat	—	Annular	—	—	—	Photo plate			—	{30 60}	— 2}	0·01	—
90	Hull, L. M. ..	1921	(Own)	—	—	13·6	Flat	—	Annular	—	0·01	—	Flat	(4¾)	—	4 to 13	10	—	0·011	—

TABLE 8.*

Properties of Electron-Jet Instruments.

Hot Cathodes.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Ref. No.	Authority	Date	Details of instrument													Discharge			Measured sensitivity	
			Maker	Overall length	Distance, cathode to anode	Distance, diaphragm to screen	Cathode		Anode		Diaphragm		Recording			Vacuum, millionths of an atmosphere	P.D.	Current	Electric, cm per volt	Magnetic, cm per gauss
							Type		Type	Diam.	Size of hole	Diam.								
				in.	in.	in.				in.	in.	in.					kV	mA		
94	Knipp and Welo ..	1915	(Own)	16	—	—	Lime spot		Ring	(4)	No diaphragm		Internal photo plate			—	1	—	—	—
96	Samson, C.	1918	(Own)	40	2	—	Plain W		Annular	—	0·04	—	Fluorescent screen			—	to 9	—	0·023	—
90	Hull, L.M.	1921	(Own)	—	—	15	Plain W and coated		Annular	—	0·01	—	Fluorescent screen			—	0·5	—	0·25	—
100	Johnson, J. B. ..	1921	W. E. Co.	10	0·04	7	Coated		Tube	0·04	(0·04)	—	Fluorescent screen			6·5 (argon)	0·3	0·5	0·1	—
97	Keys, D. A. ..	1921	(Own)	—	—	—	Plain W		Tube	¾	—	—	Internal photo plate			—	5	—	0·02	—
99	Wood, A. B. ..	1923	(Own)	—	—	—	Plain W and coated		Tube	—	—	—	Internal photo plate			—	3	—	—	—

* Extracted from a Report to the British Electrical and Allied Industries Research Association.

1 mm diam. Further, the cathode used was a W-shaped platinum wire, coated over its whole surface with barium oxide or calcium oxide (lime).

In these instruments, both types using the Wehnelt oxide cathode, the gas pressure was reduced to its lowest limit, thus eliminating ionization. Hull states that the most important advantage of the coated type of filament for use in the electron-jet instrument is the smaller amount of light emitted, combined with a bountiful supply of electrons.

In the hot-cathode instrument developed by Johnson * (1921) the cathode (see Figs. 36 and 37) is a short platinum ribbon bent into a circle, with an oxide coating of the kind described by Arnold † (1920).

Due to the presence of gas (argon at about 10 millionths of an atmosphere) employed for a special method of focusing (see Section VI, C, 2), precautions have to be taken against the development of an arc discharge. To achieve this the electrodes are enclosed in a glass mounting of small volume (1 cm^3); by this means all the paths between the electrodes are made so short that the ionization cannot build up to an excessive amount. As a further precaution a stabilizing resistance (of a few thousand ohms) is connected in the anode circuit. Further, positive ion bombardment is found to destroy the activity of the oxide coating on the cathode very rapidly; to minimize this a metal shield is placed in front of the filament, this latter being shaped into a loop so that it lies just behind the edge of the hole cut in the shield. The filament is thus protected from the "direct" bombardment and its average life is extended to about 200 hours.

The anode used is tubular, with a bore of 1 mm and a length of 1 cm; its inner end approaches within ½ mm of the shield in front of the filament, and it forms the only outlet from the confined electrode chamber to the rest of the apparatus; the electrons therefore are shot out along the bore of the anode to form the jet—hence the name "electron gun" applied to the electrode assembly.

Two pairs of deflecting plates are provided, and these are made of german silver to reduce eddy-current effects should it be desired to use magnetic deflection. Again, owing to the gas present, and the ionization caused by the jet, these plates pick up certain amounts of the discharge current, varying according to their potential with respect to the anode; the instrument thus constitutes a load of varying amount on the circuit on which measurements are being made, and in certain cases this may be a serious drawback.

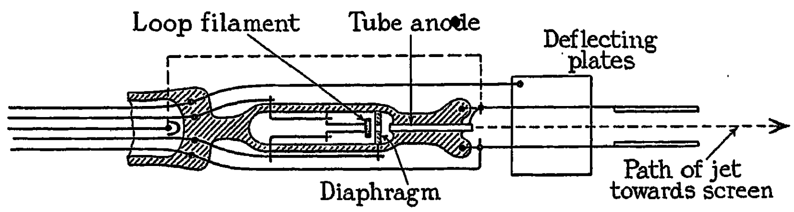


FIG. 36.—Electron gun of Johnson's tube.

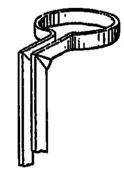


FIG. 37.—Coated platinum filament of Johnson's tube.

Jones and Tasker * (1924) developed an instrument having an arrangement of electrodes (see Fig. 38) similar to that of Johnson, except that it was not necessary to mount them in a confined space (mercury vapour at a lower pressure, about 3 millionths of an atmosphere, was used in place of argon).

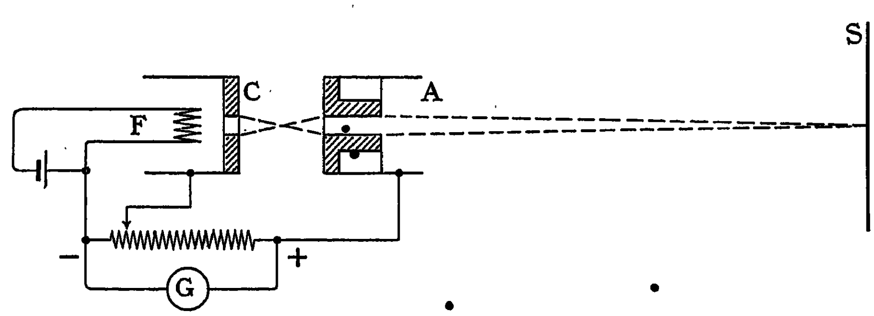


FIG. 38.—Electrode arrangement of Jones and Tasker.

The operation of the instrument was different, however, in that an auxiliary P.D. was applied between the filament and the disc in front of it; this is stated to produce "secondary electrons," formed at or near the surface of the cathode disc, the jet being drawn from these. It appears, in fact, that this disc receives most of the positive ion bombardment, since it shows signs of disintegration after prolonged use, while the oxide coating on the filament functions unimpaired. The method also gives an improved control of the focus on the jet (see Section VI, C, 2).

* See Bibliography, (100 and 101). † *Ibid.*, (102).

* See Bibliography, (103.

(VI) METHODS OF "FOCUSING" THE ELECTRON JET.

(A) INTRODUCTORY.

(1) THE NEED FOR FOCUSING DEVICES.

It will be gathered from Section I that an essential condition for the accurate working of an oscillograph or a cyclograph is that the "indicator" shall be of minimum size consistent with its visibility, or its ability to trace a record. In the case of the electron-jet instrument this means that the jet must be of as small a diameter as possible at the point where it strikes the fluorescent screen or photographic plate (see Section VII) and moreover its boundaries must be definite so that the trace made shall be sharp and clear. Needless to say this condition should be affected as little as possible by either the displacement or the velocity of the jet's deflections, within the normal working limits. Unfortunately the following causes tend to produce just the opposite condition :—

(i) The devices used for producing the electron jet (involving essentially the "source of electrons" and the "accelerating field") may not be perfect in their action, in so far as the motion given to the electrons may not be properly parallel (or convergent, see later), so that the jet commences to disperse at the commencement of its journey.

(ii) Owing to the electrons composing the jet being charged with electricity of the same sign, there is a repulsive force acting between each electron and every other. The radial component of this force is unbalanced and acts outwards (see Appendix, Section XI, B, 5); and since the jet works in a vacuum the electrons are in general free to move radially in response to this force.

(iii) In instruments using a gaseous discharge, there are bound to be collisions (not necessarily producing ionization) between the moving electrons and the molecules of gas in the space traversed; as a result the electrons will be deflected from their original courses, some more and some less, so that not only does the jet grow in diameter but it also becomes diffuse, producing a blurred trace with indefinite boundaries (see also Section III, C, 5).

(2) THE HIGH-VELOCITY JET.

In the early electron-jet instruments, developed by J. J. Thomson, Braun, and Zenneck (see Sections III, B, and IV), it was found experimentally that to produce a satisfactory jet it was necessary to use a high exhaustion and a high P.D. The explanation is to be found in the second and third causes described above. For, on the one count, the absorption of the rays is reduced by lowering the pressure of the residual gas in the apparatus; and on the other count, with a higher accelerating P.D. the velocity of the jet is higher and the time of flight of the electrons from source to screen is shorter, giving less dispersion due to the force of mutual repulsion.

The work of Dufour may also be quoted as an instance of the use of a high P.D. (up to 60 kV), though it should be stated that this value was chiefly necessitated by the requirements of recording (Section VII); the oscillograms taken with his instrument show a remarkably fine and sharp trace. The same tendency may be noted with the hot-cathode instruments (Section V).

It should be noted that even the high-velocity method fails if other factors are not prevented from influencing the behaviour of the jet. Thus Dufour (see Section IV) in trials of this oscillograph at very high frequencies (up to 220×10^6 cycles per sec.) found that increase of power beyond a certain point *decreased* the sharpness of the trace, by causing the jet to disperse, due to the increased *electron density* in the jet (see also Section XI, B, 5).

(B) ELECTROMAGNETIC METHODS.

(1) USE OF THE AXIAL FOCUSING COIL.

Other workers, however, found that even with these precautions there was still much to be desired, not merely in the size of the spot indicator, but in its intensity and sharpness. Wiechert (1898) and others * found that by applying a fairly strong magnetic field to the jet instrument parallel to its axis, the spot could be concentrated into a smaller area.

Rankin † (1905) studied the effect with the instrument designed by Ryan (see Section IV) and confirmed what others had found, viz. that application of the longitudinal field produced a large but irregular decrease in the P.D. required to produce a discharge, whilst the current passed through the apparatus was substantially unaltered. Thus by use of this focusing field it was possible to exert a large measure of control over the sensitivity of the instrument. Owing largely to its simplicity this method of focusing became standard practice with most of the workers using cold-cathode instruments.‡ The usual method of applying the field is by means of a short solenoid coil, 6 in. or more in diameter, mounted axially with the jet instrument either in the plane of its cathode or between the cathode and the diaphragm. Two coils have been tried in place of one (see also Hull, 1921); the only advantage is to lessen the tedium of adjustment of position, orientation and current strength (a range of 500 to 2 000 ampere-turns was found satisfactory).

(2) MODE OF OPERATION.

The effect of the axial focusing coil is to immerse the electron jet in a longitudinal magnetic field. Thus if the electrons are moving properly parallel, the field exerts no deflecting force on them; but if there is any divergence in the jet, the electrons will have a component of motion perpendicular to the direction of the field, and a deflecting force will result (see Fig. 39).

Suppose an electron to acquire a direction of motion inclined at an angle θ to the direction of the field. If the field is assumed uniform and parallel, and of strength H, then the perpendicular component of the electron's velocity is

$$v \tan \theta,$$

* See Bibliography, (104, 105 and 106). † *Ibid.*, (80 and 81).
‡ *Ibid.*, (82, 85, 90 and 107).

and in the Appendix it is shown to be subject to an acceleration

$$\frac{Hev \tan\theta}{m_t}$$

Now this acceleration is always perpendicular to the transverse velocity at each instant, so that the transverse motion becomes circular, the resultant motion of the electron being a helix.

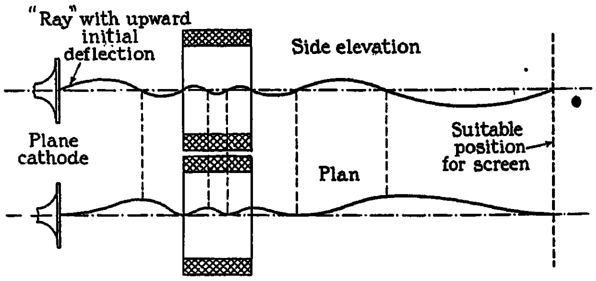


FIG. 39.—Path of electron jet with axial focusing coil.

The acceleration due to the field must obviously be equal to

$$\frac{(v \tan\theta)^2}{r}$$

where r is the radius of the component circle,

whence $$r = (v \tan\theta)^2 \times \frac{m_t}{Hev \tan\theta}$$

$$= v \tan\theta \frac{m_t}{He}$$

The component velocity in the circle, $v \tan\theta$, remains constant because the acceleration is always perpendicular to it; hence the time taken to make one revolution is

$$t = \frac{2\pi r}{v \tan\theta} = 2\pi\frac{m_t}{He}$$

and, from this, the "pitch" of the helix is

$$s = 2\pi\frac{m_t}{He}v$$

Thus after travelling an axial distance equal to this quantity, the electron reaches again the same position relative to the axis of the apparatus as that from which it started. The important point to note is that this axial distance is independent of the angle of divergence, θ.

The effect of non-uniformity of the magnetic field, such as is produced by a single focusing coil, is to cause a varying angle of helix; but the property of focusing all electrons, though of different degrees of divergence, is unimpaired. It is, in fact, possible by means of such a non-uniform field to produce a spot on the screen smaller in size than the diaphragm hole.

(3) AXIAL CONDUCTOR METHOD.

It seemed desirable to improve on the indirectness of the focusing-coil method, and to provide some means whereby the electrons might be deflected directly in a radial direction. To achieve this object a method (see Fig. 40) was devised by F. R. F. Ramsay (1923) and has been subjected to some preliminary trials by the authors at East London College.

The principle is the use of a circular magnetic field concentric with the jet; to produce this, a straight conductor is mounted in the axis of the instrument (along the undeflected position of the jet); current is led into and out of this conductor at its ends by a number of flat radial strips, and the jet is thus able to pass over the conductor close to its surface (where the field is strongest) with minimum obstruction.

When the electron flow is in the same direction in the axial conductor as it is in the jet, then the circular field is in the correct sense for exerting an inward radial force on the jet electrons, i.e. for producing a focusing effect. A disadvantage of the method is that the strength of the field, and therefore the focusing force on each electron, is inversely proportional to the distance from the conductor (axis), whereas in general the further an electron is from the axis the larger is the radial force that it requires (see also Appendix).

(C) ELECTROSTATIC METHODS.

(1) RADIAL FIELD.

Attempts have been made to focus the jet of a cold-cathode instrument by electrostatic means. The tubular portion (both sides of the anode) was provided with tin-foil coatings and these were connected to the cathode, so that there should be a mutual radial repulsion between the coating and the jet electrons. The method naturally failed, because the "potential" of an electron, when unconstrained as it is inside the vacuum, becomes that of the space in which it is situated. To explain this it should be remembered that "potential" means "potential energy," and, since an unconstrained charged body can possess no potential energy, the energy supplied by the field in space appears as a change of kinetic energy. In other words we have the conditions that *radially* there is no electric field inside the hollow conducting coating, and *axially* the field retards the electrons and brings them to rest after they have been projected by the cathode fall of potential. Connection of the coating to the anode (positive electrode) did produce an improvement in the "spot."

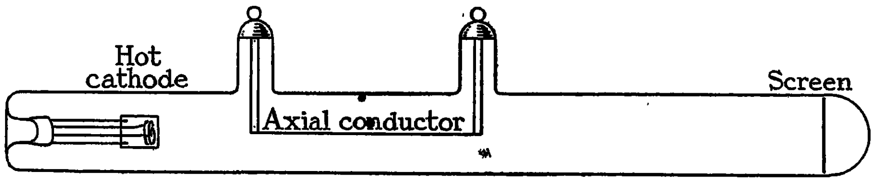


FIG. 40.—Electromagnetic focusing with axial conductor.

A correctly applied modification of this method was tried with his hot-cathode instrument by Wood * (1923, see Fig. 41). A tubular anode was used, arranged axially in the instrument, and along its axis was fixed a wire, which was charged positively with respect to the anode tube. The electrons passed along inside the anode tube. The *axial* effect of the positively charged wire was to accelerate them rather than to retard them, and the *radial* effect was to produce a radial electric

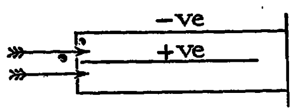


FIG. 41.—Electrostatic focusing with positively-charged axial conductor (after Wood).

field which exerted a definite focusing influence on the jet. However, on this particular instrument the method was not so satisfactory as the one finally adopted (see Section VI, D).

(2) "IONIC" METHOD.

(*a*) *Mode of operation.*

Johnson † (1922) has successfully applied a neat method of focusing, which he states was originally suggested by van der Bijl. The method appears to be a scientific development of an effect which has been more or less operative in all the hot-cathode instruments working with a very low P.D. (mostly using Wehnelt type cathodes), as described in Section V. The instrument is filled with gas (preferably of a heavy nature, see later) at a definite pressure, approximately 10 millionths of an atmosphere. As a result a small proportion of the electrons in the jet collide with molecules of the gas and ionize them. Owing to the large difference between the mobilities of the electrons and of the positive ions (especially with a heavy gas), the colliding electrons and any secondary electrons produced mostly leave the jet, whereas the positive ions drift out only slowly, with little more than their comparatively low thermal velocity. The positive ions therefore tend to accumulate down the length of the jet, and a point can be reached where the number of positive ions in the jet considerably exceeds the number of electrons therein. The jet thus becomes positively charged with respect to the surrounding gas and the glass walls of the instrument, and there is established a strong radial field of the correct sense to exert an inward radial force on the electrons within the jet.

At the point where the positive ions and the electrons are equal in numbers, the mutual repulsion of the electrons is just neutralized; and with the positive ions in excess of the electrons a definite focusing effect is obtained. Johnson calculates that if in his instrument the jet has an initial divergence of 1°, and carries a current of $20\mu A$, the jet will be focused at the screen when there are four positive ions in the jet to each electron, giving a radial field of 1 volt/cm. Measurements in a special apparatus with one jet perpendicular to another gave a value for this radial field of 3 volts/cm.

* See Bibliography, (99). † *Ibid.*, (101).

(*b*) *Advantages and limitations.*

The great advantage of this focusing method is the fact that the action on the jet is continuous throughout its length, not interfering with arrangements for deflection of the jet. It should be noted, however, that there is a definite time factor in the establishment of the positive ionization within the jet, and this leads to the disadvantage that if the jet is deflected too rapidly through the gas space the ionization fails to build up to the proper value, since the ions are produced at points along the jet, and are not travelling longitudinally with the electrons. Thus from the figures given in Johnson's paper the focusing action is found to fail as the "velocity of traversal" of the fluorescent spot reaches 100 km/sec.

An additional convenience is the ease of adjustment of the focusing action, for it is found that variation of the filament temperature, which controls the current in the jet, suffices to control the magnitude of the radial field, and hence the distance along its path at which the jet comes to a focus. Now it is shown in the Appendix that the dispersive force on an electron is

$$\frac{2e}{kv}\gamma\frac{I}{R_0}$$

so that with v, γ, and R_0 constant, the force is proportional to the current I in the jet. Johnson states that increasing the jet current causes the jet to focus in a shorter distance; from this it would appear that the positive ion density in the jet increases at a faster rate than the electron density.

In the apparatus of Jones and Tasker * (1924) the jet is focused twice, once between the cathode and the anode, and again at the screen. This confers a further advantage in the operation of the apparatus, for control of the exciting P.D. (applied between the filament and the cathode disc) varies the position of the first focus, and hence the diameter of the jet as it passes the hole in the anode, and so constitutes a control over the focusing of the spot on the screen, this control being independent of the filament temperature adjustment.

(D) "GEOMETRICAL" METHODS.

(1) CONICAL JET.

The methods described under this heading mostly employ some magnetic or electrostatic principle of operation, but are designated "geometrical" because they depend more on controlling the initial direction of projection of the electrons than on applying deflecting forces to them after their formation into a jet.

For example, Wood † (1923) suggested using as anode a number of fine tubes, mounted symmetrically around the axis of the instrument and pointing towards a common point thereon. With this arrangement the jet is composed of the electrons travelling through these tubes, and hence in convergent directions (see Fig. 42).

A similar idea due to E. B. Wedmore (1923) is to use as anode a hollow cylinder or hollow zone of a cone, partially filled with a concentric solid cylinder or cone so as to leave a thin annular space through which the electrons pass. Thus instead of a thin cylindrical jet,

* See Bibliography, (103). † *Ibid.*, (99).

as in Braun's instrument, or a number of convergent jets as in the method above, the form taken by the jet is that of a thin-walled tube. By suitable choice of the angle of the cone, the jet may be brought to a focus at any desired point along the axis. The chief objects of the device were to render possible the use of focusing methods in which the radial force exerted on the electron is dependent upon its distance from the axis, and to obtain a larger current in the jet.

(2) CONCAVE CATHODE.

A more direct method is the one applied in the earliest days in cold-cathode ("gas") "X-ray tubes" by Crookes (1876) and later by H. Jackson, viz. giving the cathode a smooth concave surface on the side facing the "target." Thus by virtue of the property of "normal emission" [see Sections III, A, 3, (*b*), (ii) and III, A, 2] the electrons are given initial directions converging on the centre of curvature of the cathode surface and, by placing the target rather beyond this point, allowance is made for the natural dispersion of the electrons (Section VI, A) and the target receives the jet while it is of minimum diameter.

This method has been applied to the cold-cathode electron jet instrument by Hull * (1921), while Wood †

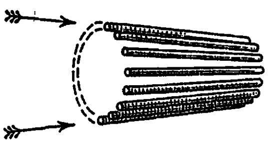


FIG. 42.—Geometrical focusing with inclined tubes (after Wood).

(1923) has suggested using a concave hot cathode, to be kept hot by electron bombardment from an auxiliary cathode. This idea should prove successful if a gaseous discharge is being used for production of the electron jet, for then the "space charge" of the positive ions gives rise to a sudden potential drop at the concave surface of the cathode. If, however, a pure electron discharge is to be used (as was done in Wood's final instrument) the fall of potential occurs at the anode (due to the electronic "space charge") and the concave shape of the cathode surface would not confer so great an advantage as with the gaseous discharge (see also next Section, VI, B, 3).

(3) COOLIDGE'S HOT CATHODE.

A method similar in principle but not dependent on a "cathode fall," and applicable to hot filament cathodes, has been developed primarily by Coolidge ‡ (1913) (see Fig. 30) for his hot-cathode X-ray tube. The filament (of bare tungsten wire) is wound into the form of a flat ("pancake") spiral, and is mounted just inside a cylindrical "hood" to which it is electrically connected, its plane perpendicular to the axes of the hood and the tube. The amount of projection of the hood beyond the spiral filament is found to control the focusing effect produced. In this tube a pure electronic discharge is used, and the "anode fall" due to the space charge is a negligible proportion of the total P.D. owing to

* See Bibliography, (90). † *Ibid.*, (99). ‡ *Ibid.*, (75).

the high values used (up to 100 kV), therefore the axial distribution of potential will be approximately uniform. But, due to the projection of the hood over the filament, the direction of the electrostatic field in the immediate neighbourhood of the filament is strongly convergent, and this determines the initial direction of the electrons; thus although *axially* the electrons are being accelerated approximately uniformly, they retain the inward *radial motion* given to them at the start (see Figs. 43 and 44).* The hot-cathode electron-jet instruments used by Keys † (1921) and Wood ‡ (1923)

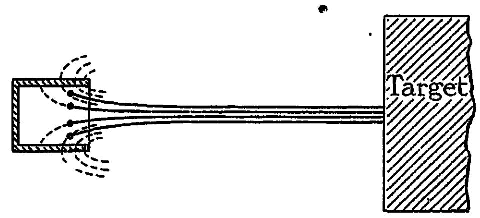


FIG. 43.—"Fine" focus with Coolidge cathode (after Warren).

have Coolidge type cathodes, in conjunction with a "pinhole tube" anode.

(VII) METHODS OF INDICATING AND RECORDING.

(A) WITH FLUORESCENT SCREEN.

(1) VISUAL INDICATION.

(*a*) *Nature of fluorescent material.*

Crookes (1879) and Thomson (1897), we have noted, relied upon the fluorescence of glass for indicating the deflection of the electron jet.

In 1895 Perrin,§ in measuring the charge carried by the rays, used a transverse magnetic field to control

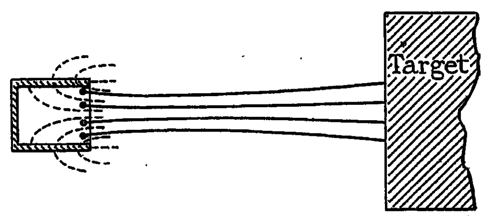


FIG. 44.—"Broad" focus with Coolidge cathode (after Warren).

the entry of the rays into the measuring cylinder (Faraday cylinder); as an independent check the surface of the guard cylinder was coated with a fluorescent powder, and the resulting luminous area indicated the displacement of the rays.

Braun ‖ (1897) was, however, the first to use a fluorescent mineral in an electron-jet measuring instrument. The material he used was willemite (anhydrous crystalline zinc silicate, Zn_2SiO_4) which in his tube showed a bright green colour under bombardment. The material was in the form of a fine powder laid upon a disc of mica which was mounted in the tube as shown (S, Fig. 14).

Zenneck ¶ (1899) made a comparison of the merits

* Also see Bibliography, (108). † *Ibid.*, (97). ‡ *Ibid.*, (99). § *Ibid.*, (46 and 47). ‖ *Ibid.*, (68). ¶ *Ibid.*, (77).

of calcium sulphide and calcium tungstate. Under very intense bombardment CaS gives a fluorescent light which is nearly white, the photographic effect of which is at least equal to that of the blue-purple fluorescence of $CaWO_4$. With weaker bombardment, however, such as that which occurs with average discharge in the cathode-ray tube, or with the fluorescent spot in rapid motion over the screen, the luminous effect of CaS, now a bright green, is still stronger than that of $CaWO_4$, but the photographic effect in much weaker.

Varley * (1902), who used a tube similar to Zenneck's, chose calcium tungstate as the fluorescent material for visual observations.

Morris † (1902) in an English-made tube used zinc silicate for visual work.

In 1909 Giesel and Zenneck ‡ investigated the use of zinc sulphide as a fluorescent material in the Braun tube. This substance gives a blue-green fluorescence, a colour not so powerful visually as the yellow-green of calcium sulphide and zinc silicate; nevertheless the zinc sulphide was found to be more sensitive under the weak bombardment resulting from rapid traversal of the jet over the screen. The substance also gives a distinct afterglow, and this contributes materially to the resultant effect when the jet is tracing a large figure.

Chaffee § (1911) found that a very sensitive screen for visual work could be made by dusting finely powdered willemite over a piece of mica or glass freshly painted with a thin coat of waterglass, but for photographic recording he used zinc sulphide.

Minton ‖ (1915), Hull ¶ (1921), Johnson ** (1922), and Wood †† (1923) recommend zinc silicate (Zn_2SiO_4) for visual work, since it gives a bright green colour, and calcium tungstate ($CaWO_4$) for photography since its blue fluorescence is rich in actinic rays. Johnson in his hot-cathode instrument uses a mixture of half of each, thus combining their advantages and obtaining a fluorescent layer more than half as bright visually as plain zinc silicate, and more than half as active photographically as plain calcium tungstate.

(*b*) *Form of screen.*

Braun's screen, the purpose of which was to carry the fluorescent layer, was a flat circular disc of mica. Mica was used because it is light and rigid, is easily mounted in position, will withstand the heat of the glassworking in constructing the instrument, and has no adverse effect on the vacuum conditions. Later glass was used in place of mica, by Varley (1902, loc. cit.); it has the advantage of greater transparency, allowing the cyclogram figure to be viewed from either side of the screen. The importance of this for recording by photography was pointed out by Rankin.‡‡

The theory of the deflection of the electron jet (see Appendix) shows that when the deflecting field is finite in extent so that the jet travels across a free space before reaching the screen, then the correct shape for the screen surface is a plane, oriented in such a way that the undeflected or zero position of the jet is a normal to the plane. Further, if deflection is obtained by immersion of the whole jet instrument in the field, this rule still holds when the field is electrostatic; but when it is magnetic [see Thomson * (1897), Knipp and Welo † (1915), and others] it is no longer mathematically accurate. However, in all the jet instruments so far described the maximum angular deviation of the jet that can be recorded is limited, and the error introduced by the use of a flat screen in such a case is well within the limit of accuracy of the instrument.

It has been found convenient to dispense with a separate screen, the fluorescent layer being mounted directly on the inner surface of the vacuum vessel, when this is of glass. This has the advantage of simplifying the construction of the instrument, and further, it favours photographic recording from the rear of the screen [see Section VII, A, 3, (*b*)]. Now in portable instruments, such as that designed by Johnson ‡ (1922), this surface must necessarily possess considerable curvature, and this produces a distortion of the record. Johnson expresses the error of his instrument in the following terms: If the pattern is recorded by a camera whose lens is 2 cm from the end of the tube, the apparent reduction of deflection produced by curvature of the bulb is given in terms of the deflection γ approximately by

$$\partial\gamma = \frac{20 + D}{400D}\gamma^3 \text{ cm } §$$

(2) MEASUREMENT OF DEFLECTION.

When an electron-jet instrument is used with linear deflection for measuring a steady quantity, a measure of the deflection of the indicator spot, in terms of length, is sufficient information. In Thomson's instrument the indicator line moves on the glass, and the desired result is quite simply obtained by attaching a bent scale to the glass and reading off the deflections, as in an ordinary measuring instrument with mechanical pointer and scale. On the other hand, when the indicator is a fluorescent spot on a screen, mounted inside the tube, such direct reading is not possible unless the screen itself is provided with a suitable scale.

Varley ‖ (1902) made direct measurements of deflection (linear) on the internal screen of his Braun's tube by optically projecting a scale on to the screen—the scale was cut in tin-foil on glass, strongly illuminated from behind, and the lenses were arranged to give exactly millimetre divisions on the screen. Later, however, the instruments made by Müller-Uri were provided with glass screens carrying a "graticule" of uniform millimetre squares engraved on the uncoated side.

(3) RECORDING DEVICES.

(*a*) *Manual.*

(i) *Ruled screen method.*—With two-dimensional working it is preferable to secure a separate copy or record of the oscillogram or cyclogram, upon which measurements may be made of angle, area, etc., as well as of length. The graticule or ruling on the fluorescent screen provides a ready means for making such a copy, for if a copy of the graticule is available on a sheet of paper, the figure may be drawn in, freehand, with an

* See Bibliography, (109). † *Ibid.*, (1). ‡ *Ibid.*, (110). § *Ibid.*, (84). ‖ *Ibid.*, (85). ¶ *Ibid.*, (90). ** *Ibid.*, (101). †† *Ibid.*, (99). ‡‡ *Ibid.*, (81)

* See Bibliography, (67). † *Ibid.*, (93). ‡ *Ibid.*, (101).
§ This formula refers only to the particular instrument designed by Johnson.
‖ See Bibliography, (109).

accuracy at least as good as that of the figure as it appears on the screen. If the screen is ruled with uniform squares, ordinary squared graph paper may be used for the copy; this can be obtained with different sizes of squares, and hence a magnification or a reduction in size of the figures may be made if desired. Similarly with a non-plane fluorescent layer, any approximately uniform lines may be marked upon it and the resulting graticule photographed, the copy of the figure being drawn on a photographic reproduction of the graticule.

The process is not very rapid, and necessitates the figure remaining accurately steady on the screen during the copying; on the other hand, the measurements required may often be obtained by copying portions only of the figure—thus speed and accuracy may be combined.

(ii) *Tracing desk method.*—An alternative method of making the copy, more complicated but possibly more accurate, is to trace it on a lightly-smoked glass plate, the eye being kept in a fixed position during the process. This method was the one adopted by Ryan * (1911). The record was made from the front or coated side of the fluorescent screen; but distortion due to the necessarily angular view was eliminated by placing the tracing plate parallel to the screen. This plate is mounted over an aperture in the bottom of a shallow light-tight box lined with white paper; a corresponding aperture in the top admits the tracing point, and the open end admits light from a lamp so that the tracing point and the traces made shall be visible without light being thrown on the screen of the cyclograph.

(*b*) *Photographic.*

(i) *With camera.*—Zenneck † (1899) recorded his cyclograms by photography with an ordinary camera and sensitive plate, the tube and camera being darkened to prevent reflection of extraneous light by the screen or the glass of the tube. The exposure time necessary with normal operation of the instrument was about 10 minutes. This time could be shortened by using a stronger discharge (the exciting machine being run at its maximum speed), 6 to 20 secs. being required for recording a cyclogram, and 1 to 2 secs. for the stationary spot. It has been noted, however, that satisfactory operation of the cyclograph was not obtainable with this heavy discharge.

Ångström ‡ (1900), using a tube made to Braun's specifications, adopted the same method; half-size photographs of the cyclograms were obtained with 10 to 20 seconds' exposure.

Ryan § (1903) who obtained a larger tube and ran it with a heavy discharge was able to secure satisfactory photographs with an exposure of 2 to 5 secs. Such records are faint but sufficiently visible, and are therefore the best as they give the finest trace and so make for accurate measurements. For reproduction purposes, and especially for making lantern slides, the exposure must be considerably longer to secure sufficient contrast; this results in a much broader and more indefinite trace.

* See Bibliography, (82). † *Ibid.*, (77). ‡ *Ibid.*, (111). § *Ibid.*, (79).

Rankin * (1905) points out that in the tube used by Ryan the screen was made of a thick quality of mica, and since the photographs were taken from the back of the screen the mica would account for a considerable absorption of the actinic rays.

Varley and Murdoch † (1905), using a Braun tube having a calcium tungstate screen taking $0{\cdot}02\mu A$ with 4 mm equivalent spark-gap, obtained records with exposures of 20–30 secs.

Chaffee ‡ (1911) photographed the front (fluorescent) side of the screen, obtaining natural-size records with exposures of 3–30 secs.

Zenneck § (1913), who passed 0·5mA at 28kV through his Braun-type tube, and Samson ‖ (1918), who with a hot cathode used a tube current of up to 10mA at 9kV, obtained records on moving plates, i.e. with only a single traversal of the indicator (image of fluorescent spot).

Johnson ¶ (1922), by using a hot (coated filament) cathode and a special focusing method, combined with a sensitive fluorescent layer, found 20 secs. sufficient exposure for an average repeated-trace cyclogram, in spite of the low velocity of his jet; a "modulation diagram," in which the indicator has to cover an area to indicate its envelope, required an exposure of 2 mins.

(ii) *By contact photography.*—This method is applicable only to those instruments in which the fluorescent material is on the inner surface of the glass wall of the tube. The principle is to apply the light-sensitive film in contact with the outer surface of the same glass wall; then the film is acted upon by light directly radiated from the fluorescent layer. The trace obtained on the film will naturally be considerably broader and with more indefinite edges (like a penumbra effect) than the light trace on the fluorescent layer; but in practice the loss of accuracy on the record will not be great, unless the glass is unusually thick. It may be noted that of available instruments, that developed by Johnson lends itself well to this method of recording, for its glass is thin and of uniform thickness over the fluorescent area. The loss of accuracy may in fact be partially compensated by the shorter exposure possible, on the lines of Ryan's experience [see Section VII, A, 3, (*b*), (i)], for evidently the proportion of the light emitted by the fluorescent material that acts on the sensitive film is enormously greater with the contact method than it is when a camera and lens are used.

One way applicable when the curvature to be accommodated is not too great is to use a gelatine film stretched across a light frame instead of being mounted on celluloid or glass, carrying the sensitive emulsion in the usual manner. This film will be elastic and will fit against the curved glass surface of the electron-jet instrument, giving the necessary contact. When the exposure is completed the film will regain its flat shape, so that contact prints may be made from it on ordinary flat paper. Obviously such a film requires very careful handling in all the stages from manufacture to the final print; and a further cause of unreliability is the distortion of the record due to imperfect elasticity and the wetting and drying of the gelatine. An improve-

* See Bibliography, (81). † *Ibid.*, (112). ‡ *Ibid.*, (84). § *Ibid.*, (113). ‖ *Ibid.*, (96). ¶ *Ibid.*, (101).

ment on this is to prepare a plaster cast of the curved glass surface, and mount the sensitized gelatine film on the surface of the cast—for example, it may be manufactured in situ by the wet-plate process. With this device distortion of the film is eliminated, and it is possible to establish contact over the full area, unrestricted by the curvature of the surface. To prepare a flat record it is necessary to resort to the use of a camera and photograph the negative (which is on the plaster cast); thus almost the same result is obtained as though the trace on the fluorescent layer had been photographed with a camera, but the long exposure part of the process has been eliminated.

With either of these methods it is necessary to make allowance for the distortion of the cyclogram due to the curvature of the fluorescent layer, should the amount of error be not negligible [see also Section XI, A, 1, (*b*)]. A convenient method when linear dimensions of the cyclogram are required is to make the apparatus prepare its own graticule—one component deflection is made an alternating motion, while the other is held at a number of standard values of deflection in turn; then this process is repeated with the component deflections interchanged. The flat record obtained from this is superimposed upon the cyclogram with the axes coinciding correctly, and is used as the scale from which measurements are read.

(B) With Internal Photographic Plate.

(1) General.

The methods of recording that have hitherto been described (see Section VII, A) take time to accomplish; hence they are on a par with the step-by-step methods of determining wave-form, in so far as they are applicable only to periodic phenomena which can be held sufficiently constant during the time of recording. In general such procedure is inapplicable to the recording of transient phenomena. Dufour * (1914) suggested that it would be necessary to have an arrangement of apparatus permitting direct registration of the electron jet on a photographic plate. Even with direct registration he found that for high-frequency work it was essential to use a much more intense electron jet (see Section IV) than that obtained in tubes of the kind used by Braun, Zenneck, etc., in order that a single traverse of the jet might leave a readable trace; and, further, constancy of the jet itself became an essential condition.

(2) Modifications in the construction of the instrument.

In the electron-jet instrument, as it has so far been developed, the jet operates only inside the vacuum chamber—hence if it is to impinge directly on a photographic film this film must also be mounted inside the vacuum chamber. The method of mounting the film or plate depends upon the time scale in use (see Section VIII)—thus a rotating drum may carry a film, winding spools may carry a roll-film, or a magazine may carry a film-pack or a number of plates. In each case it is usual to arrange the whole mechanism inside a light-tight box or camera, so that the instrument is made daylight loading.

* See Bibliography, (87).

The first requirement is that the vacuum chamber shall have a door which will admit this camera when open, and which can be made vacuum-tight with a minimum of trouble when closed. Secondly, if the time-scale motion is imposed on the recording surface, a suitable drive must be fitted [see Section VIII, C, 2, (v)]. Thirdly, means must be provided for changing the plates of a magazine, or for winding a roll-film, and for opening and closing the shutter of the camera. This shutter is of the same size as the recording area and, when closed, lies parallel to it; it frequently carries a fluorescent coating, so that the instrument may be operated visually when required. The details of construction and the technique of operation of this accessory apparatus have been developed largely by Knipp and Welo * (1915), Dufour † (1920), Keys ‡ (1921), and Wood § (1923).

In addition to these modifications in the construction of the instrument, it is necessary to have it permanently connected to an exhausting plant, since the vacuum is lost each time the instrument is opened. As a result it is no longer possible to make the instrument portable, and the total cost of the plant is considerably increased. In the matter of convenience in use, with modern exhausting equipment it is possible to evacuate the instrument ready for use in a comparatively short time—Dufour on his oscillograph (using a mercury-vapour diffusion pump) obtains sufficiently rapid working to enable 4 to 6 films (from the rotating drum) or 20 to 30 plates to be exposed in an afternoon.

(3) Sensitivity of the photographic plate to cathode rays.

The problem of recording on a photographic plate by direct activation by the cathode rays may in a sense be regarded as opposite in nature to that of recording the impact of X-rays. A normal photographic plate, working with light rays, absorbs a high proportion of the energy of the light falling upon it, and a good proportion of this absorbed energy is useful in activating the silver salt in the emulsion. Now the tendency with X-ray work, and especially with "hard" rays, is for the rays to penetrate through the plate, so that only a small proportion of the incident energy is absorbed by the sensitive emulsion. To absorb a higher proportion of the incident energy, and secondly to transform this as much as possible into a form that will activate the emulsion, different devices have been adopted, such as thicker and double emulsions; loading with lead and thorium salts, whose "soft" characteristic radiations are excited and add their blackening effect; and coating with fluorescent material (sometimes on a separate carrier, making an "intensifying screen," placed behind the plate), which adds its light radiation.

With cathode rays, on the other hand, the rays are too readily absorbed by the plate. In an average cold-cathode tube the penetration of the rays into the gelatine film is of the order of 0·02 mm, so that only

* See Bibliography, (93 and 94). † *Ibid.*, (88 and 89). ‡ *Ibid.*, (97). § *Ibid.* (99).

a small proportion of the silver can be affected by the rays. Further, the incident energy is expended only partly on silver granules, which is where it is wanted; the remainder is absorbed by the gelatine. Thus Dufour finds that there is little advantage in sensitivity to be obtained by using fast plates rather than slow ones, whereas they have the distinct disadvantage of being more liable to "fogging" by stray radiation. Wood * (1923) confirms this (ordinary plates of about 150 H. and D. were usually employed), and finds further that "Schumann" plates give greatly superior results—a visible photographic impression is obtained with a "velocity of traversal" of the jet across the plate reaching 1 000 m/sec., whereas with ordinary plates the records appear rather faint when the velocity of traversal exceeds 50 m/sec. (the accelerating P.D. producing the jet was 3 kV). The Schumann plates were developed originally for work with ultra-violet radiation, for which the absorption problem tends in the same direction as that for cathode rays: they are made with a minimum quantity of gelatine, so that all the active silver shall be contained in a very thin surface layer, and hence lie within reach of the quickly absorbed incident radiation. The use of the Schumann type of plate is all the more desirable with the low-velocity jets of hot-cathode instruments, on account of their smaller penetrating power.

An additional method of obtaining increased sensitivity of a photographic plate to cathode rays is to use fluorescent material (as has been done for "hard" X-rays, see above).

Levy, West, and Baker † used calcium tungstate dusted over an ordinary photographic plate, and exposure was made in the usual manner. Wood had plates made with calcium tungstate mixed in with the sensitive emulsion. The improvement in sensitivity over an ordinary untreated plate approaches the same order as that obtained with the Schumann plate.

It may be remarked here that from the use of a fluorescent layer next to the sensitized film on the plate it is only one stage to arrive at the method of Section VII, A, 3, (*b*), (*ii*), where the light radiation from the fluorescent material has to travel through the glass wall of the vacuum chamber before acting on the sensitive film.

Experiments have also been made, with some degree of success, to render plates insensitive to light whilst retaining maximum sensitivity to cathode rays. With such plates all operations, including development, can be carried out in subdued white light.

(VIII) TIME SCALES FOR OSCILLOGRAPHIC WORK.

(A) Cyclographic Method.

With the exception of the electron-jet oscillographs of Dufour, Keys and Wood, which use internal photographic plates for recording, the indications given by the electron-jet instruments that have been described are not powerful enough to imprint a satisfactory trace on any recording device with only a single transit of the indicator. From this arises the necessity of using repetition devices for the time scales, i.e. the indicator must be caused to repeat its trace on the recording plate, if possible with close accuracy, for as long a time (as many cycles) as may be necessary, just as with the cyclograph operated by two periodic quantities of integral frequency ratio (see Section I).

The simplest method is to use the instrument as a cyclograph, arranging, however, that the time-variation of the second deflecting field acting on the jet is known, or may be independently determined. This was the method adopted by Ryan * (1903), who used a pure simple harmonic motion for his time scale. The second deflecting field was produced by a solenoid, and this was fed from the a.c. mains supplying the test apparatus, through a filter consisting of a large inductance in series with a parallel oscillatory circuit which was tuned to resonate with the fundamental of the a.c. supply. With this filter it was claimed that the reduction factor on each harmonic with respect to the fundamental was $5n^3$, n being the order of the harmonic, and 5 the amplification factor of the fundamental due to resonance. The magnetic deflection produced was thus sufficiently nearly a pure sine wave.

The cyclographic method, using a simple harmonic time-scale motion, was the one adopted by Keys † (1921), Hull ‡ (1921), and Watson Watt § (1923). The last two derived the sine-wave oscillation from triode oscillators giving variable frequency. Watson Watt, using an instrument of the type developed by Johnson (see Section V, C) found it practicable to record single-trace diagrams with velocities of traversal of the indicator reaching 0·1 km/sec. (= 225 miles per hour).

(B) "Uniform" Periodic Time Scales.

(1) general.

In studying wave-forms from rectangular oscillograms it is an obvious advantage for the instrument to use a time-scale deflection which is uniform (i.e. has a linear law of variation with time), instead of a harmonic deflection such as that described above. Such a time-scale deflection may still be periodic, for though its linear law must hold for a complete cycle of the unknown periodic quantity it may thereafter become discontinuous and repeat from the starting point after any integral number of cycles of the periodic quantity.

(2) moving screen.

(*a*) *Linear.*

As has been noted in Section I, B, 2, (*a*), the time-scale motion is frequently more conveniently imposed on the recording screen instead of on the indicator; this method is in fact the more used with mechanical oscillographs.

Provided that a circular motion is used, the method lends itself well to periodic work, since the motion may be directly synchronized with the periodic quantity. Thus for an electron-jet oscillograph the sensitive film on which the record is made is wrapped around a drum, which is rotated in synchronism as above stated.

* See Bibliography, (99). † *Ibid.*, (114).

* See Bibliography, (79). † *Ibid.*, (97). ‡ *Ibid.*, (90). || *Ibid.*, (116).

The axis of the drum is set parallel to the direction of the deflection of the indicator due to the electrical quantity investigated, so that the rotation of the drum supplies the required relative motion, linear and perpendicular to the first component.

(*b*) *Circular.*

An even more convenient variation of this method is to use a flat sensitive film or plate, rotated about an axis perpendicular to its plane; the plate replaces, or is arranged parallel with, the fluorescent screen of the electron-jet instrument, as with the previous arrangements. The rotation must be synchronized just as with the rotating drum. The relative motion between plate and indicator is in this case circular, and this method is the one most used for obtaining circular and polar oscillograms. Its application to a mechanical oscillograph has been carried out by Chubb * (1914) and to an electron-jet oscillograph by Grix † (1921).

Any of the photographic methods of recording described in Section VII may be used in conjunction with the moving-plate method, equally with the fixed-plate methods, provided only that provision can be made for moving the recording surface in the manner specified above. For example, the use of internal photography on a rotating drum, working inside the vacuum chamber, has been developed by Dufour (see Section VIII, C, 2).

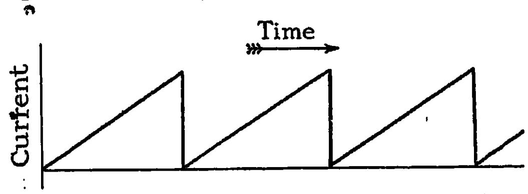


FIG. 45.—Oscillogram of Zenneck's time motion.

(3) MOVING JET.

(*a*) *Linear.*

(i) *Mechanical.*—After Braun (1897) had produced the first two-dimensional electron-jet instrument, and used it cyclographically, Zenneck ‡ (1899) proceeded to work it oscillographically. For this he imposed on the jet itself a time-scale motion that was uniform and periodic, the other component deflection being under the control of the unknown quantity; thus with proper synchronization of the time-scale deflection the recording screen showed a stationary oscillogram to rectangular co-ordinates (see Fig. 45).

To obtain this time-scale motion the jet was deflected magnetically by a solenoid coil. A revolving insulating disc, carrying a potentiometer slide wire on its edge, controlled the current in the coil, this being connected between a brush rubbing on the wire and one of the two brushes leading current to the wire (through slip-rings to which its ends were connected).

(ii) *Electrical.*—A purely electrical method of producing a uniform, periodic motion of the jet was devised by Rogowski § (1920). The electrostatic deflection of the jet was controlled by the P.D. across a condenser, and this P.D. was given a triangular wave-form (see Fig. 46) by making the current flowing through the condenser of rectangular wave-form. That is, the condenser was charged with a constant current and discharged with a constant current, this result being secured by two opposed diodes working on their saturation current; the combination is supplied with an auxiliary alternating supply whose P.D. must be large compared with that required to produce saturation in the diodes. The practical difficulties of realizing this condition of rectangular current wave-form were investigated by Rogowski and Glage.* Radio receiving valves were found to produce better results than transmitting valves, due to their saturation current being reached with a lower P.D. between anode and filament. Note from Fig. 46, for which the two diodes are assumed to work with equal saturation currents, that the return motion of the indicator is made with the same velocity as the forward motion, thus producing a second curve the opposite way round to the first. This can be eliminated by means of an interrupter, synchronized with the auxiliary supply, causing the indicator to trace out the zero time or axis on its return journey.

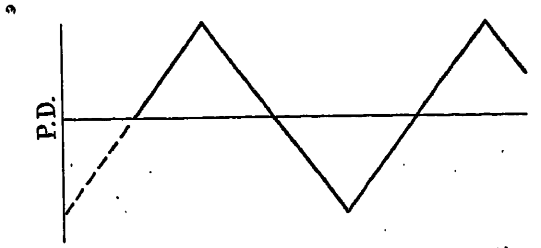


FIG. 46.—Oscillogram of Rogowski's time motion.

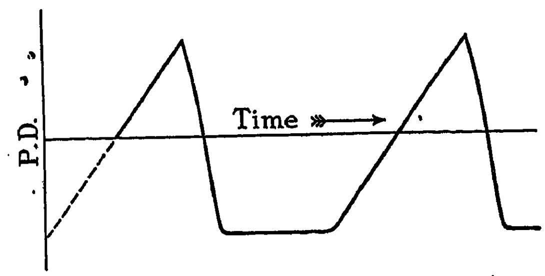


FIG. 47.—Oscillogram of Rogowski's time motion with unequal charge and discharge rates of the condenser.

Rogowski overcame the difficulty in a simpler manner, by using unequal heating of the two diode filaments. Thus the discharge of the condenser could be accomplished with a higher current, and therefore in a shorter time, than the charge (or vice versa), producing a saw-tooth wave-form of the type shown in Fig. 47. An alternative method tried by him was to allow the condenser to discharge through a spark-gap instead of through the second diode, producing a time-scale wave-form as shown in Fig. 48. This arrangement simplifies the apparatus required, but

* See Bibliography, (6). † *Ibid.*, (9). ‡ *Ibid.*, (77). § *Ibid.*, (117).

* See Bibliography, (118).

there may be complications due to high-frequency oscillations accompanying the discharge of the condenser.

If n is the number of cycles of the unknown quantity it is desired to show on the oscillogram, then each slope of the triangular wave-form must last for a time nT, where T is the time period of the unknown quantity; the time period of the auxiliary alternating supply must therefore be $2nT$, i.e. its frequency must be $1/(2n)$ of that of the unknown quantity, with the methods of Figs. 46, 47 and 48.

Another electrical method recently applied, described by Kipping * (1924), is the use of the neon-lamp oscil-

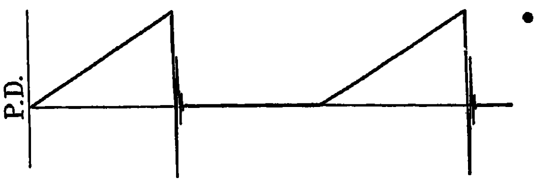


FIG. 48.—Oscillogram of Rogowski's time motion with condenser discharged by spark.

lator circuit (known also as the "flashing" or "blinking" neon lamp). In principle the method is cyclographic, for it is a P.D. oscillation derived from a potentiometer resistance in the neon-lamp circuit which produces the required time-scale motion of the electron jet. During the greater part of the time period (while the lamp is out) the current flowing into the condenser decreases according to an exponential law, but with suitable choice of the constants of the circuit and the characteristics of the neon lamp it may

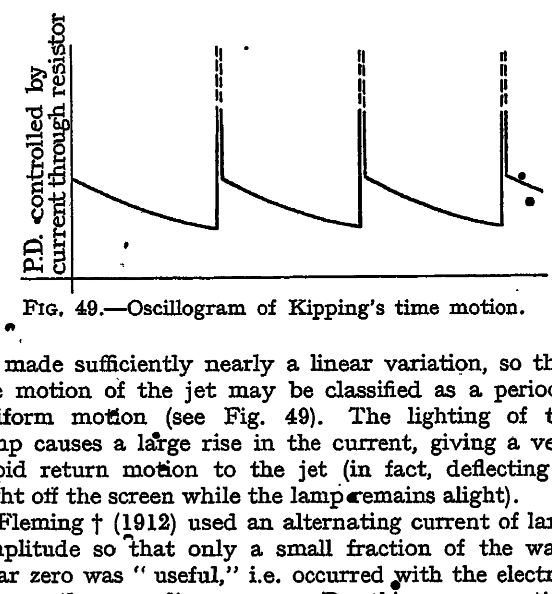


FIG. 49.—Oscillogram of Kipping's time motion.

be made sufficiently nearly a linear variation, so that the motion of the jet may be classified as a periodic uniform motion (see Fig. 49). The lighting of the lamp causes a large rise in the current, giving a very rapid return motion to the jet (in fact, deflecting it right off the screen while the lamp remains alight).

Fleming † (1912) used an alternating current of large amplitude so that only a small fraction of the wave near zero was "useful," i.e. occurred with the electron jet on the recording screen. By this means a time scale was obtained which was sensibly uniform. A method of this nature is more suited for use on transient quantities (it was in fact devised for that purpose), though this does not preclude its use for periodic quantities. To ensure that the phenomenon to be investigated would occur during the middle useful portion of the time-scale oscillation, and only once per cycle, it was controlled by a mechanically-driven commutator synchronized with the a.c. supply.

* See Bibliography, (119). † *Ibid.*, (120)

Dye * (1925) has applied this last method to periodic quantities, using the repetitions of the time scale and eliminating the mechanical interruptor. The first requirement was to separate the forward and return traversals of the jet across the screen by applying a second alternating deflecting force to the jet of the same frequency as, but out of phase with, the first one mentioned (giving the large amplitude deflection). This force was also much smaller in magnitude, so that the time-scale motion of the jet was a long, narrow ellipse, of which only the middle portion of one of the long sides was utilized. Secondly, it was necessary to secure the usual steady integral relationship (the ratio may be as high as 25) between the frequencies of the time-scale motion and the unknown quantity.

(b) *Circular.*

(i) *Mechanical.*—The time-scale component of the jet's motion may also be made circular for the production of both circular and polar oscillograms. The most direct means of doing this is to impose the circular motion on the deflecting field acting on the jet (producing in fact a rotating field). The "line of deflection" of the indicator thus becomes a "radius vector," rotating around the zero position as centre with a uniform angular velocity.

A method † for applying the circular motion in the case of an electron-jet oscillograph is as follows: The solenoid coils or condenser plates (producing a magnetic or an electric deflecting field) are mounted on hollow bearings, permitting them to be rotated about an axis coinciding with the undeflected position of the electron jet. The drive may be through chain or toothed gearing, or by a specially constructed motor whose rotor is part of the rotating deflecting apparatus; use of a synchronous motor enables the necessary integral speed relation to be obtained automatically.

It is necessary for the electron-jet instrument itself to be so designed that it can be used with this apparatus, as the jet-producing portion of it must pass at least part of the way along inside the hollow shaft of the apparatus. Further, owing to the mechanical rotation of the apparatus surrounding the vacuum tube, it is not possible to use the method for studying frequencies higher than those met with in power engineering (or in telegraphy).

(ii) *Electrical.*—As an alternative the jet may be rotated by a constant rotating electric or magnetic field. The advantage of this arrangement is the absence of both mechanical complications and inherent frequency limitation. Assuming that the resistance and the capacity may be obtained sufficiently pure, which is quite a possibility, then the arrangement in Fig. 50 (see Kipping, loc. cit.) will give the required constant rotating field (an electrostatic one) and has the merit of extreme simplicity. The necessary relation between resistance and capacity is

$$R = \frac{1}{2\pi f C}$$

* See Bibliography, (124). † *Ibid.*, (121).

where f is the frequency of the alternating supply and also the speed of rotation (in revs. per sec.) of the instrument indicator. This a.c. supply must be sinusoidal in wave-form; if necessary it may be purified by a filter such as that used by Ryan.

Note that with no unknown quantity applied to the instrument, i.e. zero indication, the indicator traces a circle; thus circular oscillograms may be obtained, but *not* polar ones. Further, both perpendicular components of deflection are occupied in producing the time-scale rotation of the indicator. The radial deflection required to give a circular oscillogram may be obtained from a deflecting device mechanically rotated in step with the indicator, but this is returning to the method just described. The radial deflection may, however, be obtained by an indirect method such as that described in the Appendix (also see Kipping, loc. cit.). In this the unknown quantity, converted to a P.D. of suitable magnitude, is added to the steady P.D. used to generate the electron jet in the instrument; this causes corresponding changes in the "sensitivity" of the jet to deflection by the constant rotating field, and the resulting changes in radius of the trace will give the required circular oscillogram when the change of velocity used is a small fraction of the constant component.

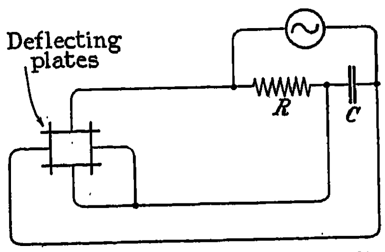


FIG. 50.—Kipping's rotator circuit.

Dye * (1925), who originated this method, used it also with a rectilinear (parallel) or a circular motion, instead of a radial one, under the control of the unknown quantity. The latter has advantages in frequency measurement work; and when the frequency ratio is high (of the order of 25, for example) the former gives an approximation to the rectangular oscillogram more simply than the radial method.

(C) "SINGLE TRACE" TIME SCALES.

(1) GENERAL.

It is obvious that the methods of recording from an electron-jet oscillograph involving the production of a stationary trace on the recording plate are inapplicable to non-periodic phenomena, and Dufour † (1914) stated that for these it was necessary to use a single-trace method, as is the common practice with mechanical oscillographs in conjunction with the "falling-plate" time scale.

After producing a form of electron-jet instrument that would give a satisfactory record under these conditions (see Section IV) Dufour devised new ways of obtaining an extended time scale (the scale factor reaching 3 km/sec., being the "velocity of traversal" of the indicator with time-scale motion only), and developed the auxiliary apparatus for applying these motions. Later * (1922) this limit was extended, the scale factor reaching 900 km/sec., enabling records to be made at frequencies up to 220×10^6 cycles per sec.

(2) MOTION IMPOSED ON SCREEN.

(i) *Sliding plate.*—Zenneck† (1913) applied the moving-plate principle to a Müller-Uri instrument—this was worked with a relatively high P.D. (28 kV) and very good oscillograms are shown in his paper. The photographic plate was carried in a dark slide which was traversed horizontally across the back of the camera by a wire wound up by a drum; the drum was driven through self-disengaging gears by an electric motor. By this means the drum, once started, made one revolution and then stopped. The drum shaft also carried a commutator which served to set in action the transient phenomenon to be investigated. The speed of the photographic plate was 1 m/sec., giving a wave-length on the record of 2 cm for a periodic quantity of frequency 50 cycles per sec.

(ii) *Rotating drum.*—Dufour ‡ (1920 and 1922) used a rotating drum for his time scale, obtaining thereby a higher velocity of the recording surface (4 to 5 m/sec.). The drum has a photographic film clipped on to its cylindrical surface which is 15 cm wide and 48·5 cm circumference. The electron jet strikes this surface normally and is acted upon by the single unknown

FIG. 51.—Dufour's time motion for low frequencies.

quantity so that it is deflected in the plane of the drum's axis. Thus a phenomenon lasting 0·001 sec. extends for 4 or 5 mm on the record; and the maximum frequency recordable is 8 to 10 kilocycles per sec. (see Fig. 51).

(iii) *Spiral trace.*—A useful modification of the method consists in superimposing on the jet a gradual traversal parallel to the drum axis (i.e. in the same direction as the unknown quantity), obtained by a magnetic field controlled through a variable resistance. This gives on the cylinder a spiral trace of considerable length and greatly facilitates the recording of transient quantities.

(iv) *Timing switch.*—On the whole, however, the better technique was found to be not to use the spiral-trace method. It became necessary then to arrange that recording should take place during only one revolution of the drum, and a "timing switch" was devised to secure this result. The shaft from which the drum is driven carries a cam and a lever which, when released by a trigger (worked by the operator), engages its pin with the cam and is carried through a cycle of operations by one revolution of the cam. This cycle commences with the switching on of power to the discharge tube generating the electron jet. Next, by means of

* See Bibliography, (124). † *Ibid.*, (87).

* See Bibliography, (89). † *Ibid.*, (113). ‡ *Ibid.*, (88 and 89)

insulated segments on the lever, on which bear brushes whose position is adjustable, the phenomena to be investigated are caused to act on the jet. The cycle closes with the switching off of the discharge tube. Thus a complete record of the phenomena may be obtained, it being possible to use the whole width of the film (length of the drum) for the amplitude of the oscillation.

The above method is described as the "first technique with the timing switch" and serves for recording wave-forms of phenomena of "low frequency" (from zero to a few kilocycles per second). Note that the drum with its film is inside the vacuum chamber, so that the electron jet impinges directly on the film surface, and the drive is by means of a magnetic clutch acting through a glass cap sealed on to the metal vacuum chamber.

(v) *Drive.*—It is not practicable to use a direct mechanical drive through a gland, because vacuum tightness must be ensured with an electron-jet instrument, and relatively high speeds of rotation are required (Dufour uses up to 600 r.p.m.). A more reliable form of drive (with which, however, the precaution mentioned below would be more necessary) is the induction-motor method; this might well be constructed on the lines of the drive to the Holweck * molecular vacuum pump. In this connection Wood † (1923) recommends

FIG. 52.—Dufour's time motion for middle frequencies.

that the magnetic or electric drive to the drum should be switched off during the actual period of recording to avoid disturbances of the jet by stray fields—the drum continues rotating by its own inertia.

(vi) *Time-scale calibration.*—Dufour uses an independent method of fixing the time scale for each record. A beam of light is periodically interrupted by an electrically driven tuning fork, and is allowed to shine on the edge of the rotating film during the period of registration (controlled in fact by the timing switch mentioned). With this arrangement no difficulty arises due to speed variation from allowing the drum to run free during the record.

(3) MOTION IMPOSED ON BOTH SCREEN AND JET.

For frequencies above a few kilocycles per second the speed of the sensitive film (on the drum surface) cannot be made sufficiently great.

The component deflection of the jet controlled by the phenomenon to be studied (called "Z") is now turned through a right angle, so that the corresponding deflection occurs perpendicular to the axis of the drum (see Fig. 52). Its place is taken by an auxiliary oscillation of the indicator (called "Y") produced by a magnetic field. This auxiliary deflection is controllable in frequency from 100 to 10 000 cycles per sec., and is given a large amplitude so that the indicator travels from end to end of the drum. In practice the power for Y is derived from a variable-speed alternator (up to 800 cycles per sec.) or from a Duddell singing arc (up to 20 000 cycles per sec. if desired). The best ratio between the frequencies of Z and Y lies between 50 and 150.

* See Bibliography, (122 and 128). † *Ibid.*, (99).

Dufour describes this method of his as the "second technique with the timing switch," and uses it for "middle frequencies" up to about a million cycles per second. It is found that the speed of rotation of the drum is still a limiting factor—a point was reached in one example shown where the auxiliary oscillation Y caused complete darkening of the film. In this example the frequency of Y was 9 000 cycles per sec., and that of the unknown Z was $1 \cdot 1 \times 10^6$ cycles per sec. Under such circumstances obviously only damped wave-trains may be investigated.

Sustained oscillations ("C.W.") may be studied if broken up into trains ("tonic train"), but the duration of each train must be less than half of the time period of Y, and the interval between trains (corresponding to "spark frequency") a considerable multiple of this period. This method was tested with Z at 150 kilocycles per sec. from an arc (Y at 2 500 cycles per sec.), using a specially-designed mercury jet interrupter giving a train frequency of 84 cycles per sec. (running at 2 520 r.p.m.).

(4) MOTION IMPOSED ON JET ONLY.

For high frequencies, of about a million cycles per second and upwards, Dufour * (1920) obtains his extended time scale wholly by auxiliary deflecting fields—the photographic plate is held stationary. The deflection Z and Y remain as before, but the relative motion of the indicator, previously produced by rotation of the drum, is now produced by a single rapid traversal of the electron jet, called "X." The method used for containing this rapid linear motion of the indicator is as follows:—The jet is first deflected well off the screen in the direction of the required traversal (to position T″, Fig. 53) with either a permanent magnet or an electromagnet. Then an air-core solenoid is excited, which gives an opposing field of twice the value; this brings the indicator to position T′. For obtaining a record, the solenoid circuit is broken, so that the indicator moves from T′ to T″.

The switch used to interrupt this circuit was a fine wire dipping into mercury and covered with alcohol; a condenser (capacity $4\mu F$) was connected across its terminals, and this with the absence of iron caused exceedingly rapid rupture of the current, so that the duration of the trace (passage of indicator across screen) could be reduced to $0 \cdot 00005$ sec.

As with the previous methods, a timing device is necessary to operate the unknown quantity and to control the high-tension power to the electron-jet instrument. For high-frequency work the latter was supplied by a step-up transformer from an alternating supply; therefore a synchronous motor was used to drive the timing device so that the instrument could be operated on the peak of the P.D. wave without necessitating the use of a rectifier or smoothing apparatus.

* See Bibliography, (88).

The method has been used for frequencies up to 70×10^6 cycles per sec; the auxiliary oscillation Y has to be of higher frequency than previously, e.g. 270 kilocycles per sec., and is supplied by a Poulsen type high-frequency arc.

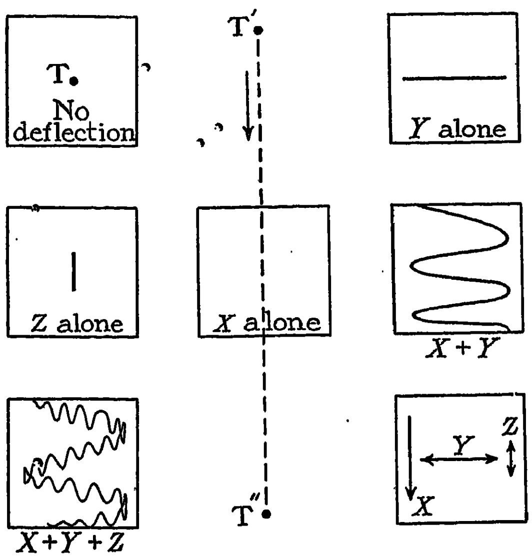


FIG. 53.—Dufour's time motion for high frequencies.

To extend the frequency range, a further stage of extension of the time-scale was tried (see Fig. 54). The deflection of the indicator caused by the phenomenon to be studied was turned through a right angle, so that it acted parallel to the auxiliary oscillation Y. Its place was taken by a second auxiliary oscillation

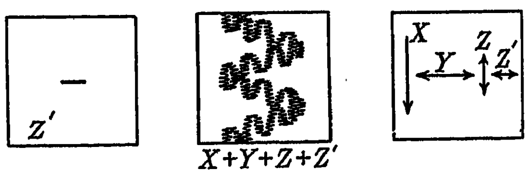


FIG. 54.—Dufour's time motion for extra-high frequencies.

(called "Z," the unknown quantity being now called "Z′") of higher frequency than Y. The power for producing Z was supplied by a Poulsen arc, up to 2×10^6 cycles per sec., for example; above this figure a spark generator was used. The method was tested with frequencies of Z′ up to 220×10^6 cycles per sec.

PART 3.

(IX) LIMITATIONS AND DIRECTIONS FOR IMPROVEMENT.

Competition with the classical types of electrical measuring instrument calls for considerably improved *deflectional sensitivity* in the electron-jet instrument, and it is to meet this demand that attention has been paid to low-velocity jets. Accompanying the use of these, however, there are two serious disadvantages, first the decrease in the *recording ability* of the jet due to its smaller power; secondly, the increased "scattering" tendency of the jet, and this not only destroys the accuracy of measurement but also detracts further from the recording ability.

The requirement here is obviously a method of focusing the jet. The problem has been solved very neatly in the oscillograph now manufactured by the Western Electric Co. In this instrument the accelerating P.D. may be as low as 250 volts, and while considerable further improvement may be still desirable this constitutes a big step in advance. Moreover, the focusing method employed in this case possesses the additional advantage of requiring an increased intensity in the jet, and this factor largely compensates for the low velocity in respect to recording ability. There seems to be no reason to suppose that the method may not be applicable to jets of even greater sensitivity.

It should be borne in mind, however, that the unique advantage of the electron-jet instrument is its faithful interpretation of electrical phenomena no matter what the frequency of variation or the steepness of wave-front; and if this characteristic is to be retained along with the improvements in other directions, alternative methods of focusing the jet must be devised. Further, unless the focusing method of itself gives sufficient improvement, it will be necessary to devise independent means for increasing the recording sensitivity of the instrument. One method that presents itself is to increase the power in the jet available at the recording screen without, if possible, affecting its sensitivity to deflection. Alternatively, the attack may be made on the fluorescent layer or the photographic emulsion to render them more sensitive to the impact of slow electrons, for example by converting a higher proportion of the incident energy into light energy. Thirdly, due to the non-proportionality between the intensity of the indication (e.g. light) and the incident energy, an improved sensitivity should be obtainable by concentrating the given total incident energy so as to give a higher energy density.

(X) CONCLUSION.

It will be seen from this survey of the subject that during the last quarter of a century there has been a vast development in the cold-cathode and later in the hot-cathode tubes, and in the technique of their application to measuring extraordinarily rapidly varying electrical quantities. Thus to-day a single transient quantity operating the tube may be seen by the eye with the spot on the fluorescent screen travelling at 225 m.p.h.; and further, with internal photography such a quantity may be recorded when the spot travels at 2 000 000 m.p.h. (i.e. 0·3 per cent of the velocity of light).

At the same time it will be obvious that finality has not been reached in this subject "Measurements in Electrical Engineering by means of Cathode Rays"; but it is hoped that future investigators may find this paper of assistance in indicating successful lines of attack.

APPENDIX.

By R. MINES, B.Sc., Student.

(XI) THE JET AS A MEASURING DEVICE.

(A) GENERAL PROPERTIES OF AN ELECTRIFIED JET.

(1) DEFLECTION OF THE JET.

(*a*) *Controlled by a deflecting field, with constant jet velocity.*

(i) *Infinite deflecting field.*—In Fig. 55 let AO represent the jet of a jet measuring instrument—it may consist of solid material particles, liquid, gas, or "non-material" particles—and let v be its constant linear velocity of projection in the direction AO. At the point O the jet emerges into the influence of a field of force, used for deflection of the jet. For the moment this field will be assumed of uniform strength and constant direction in the space to the right of O. Let the transverse component of the force acting on the jet be σ units per unit of length of the jet. Then each element of length ∂x of the jet experiences a transverse force $\sigma\partial x$. Such element, however, has a mass $\rho\partial x$. It therefore suffers a transverse linear acceleration

$$f_t = \sigma\partial x \div \rho\partial x = \sigma/\rho$$

Suppose the deflection of the jet to be observed at a point P of its path, such that it has travelled a

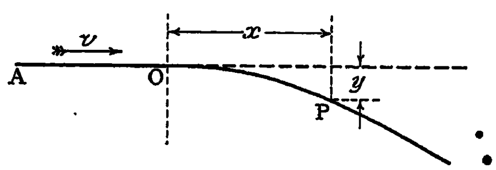


FIG. 55.—Jet entering a deflecting field.

longitudinal distance x under the influence of the deflecting field. The time taken for the element to reach P from O is x/v, and the transverse displacement that takes place during this time interval is

$$y = \frac{1}{2}\text{ (acceleration) (time)}^2 = \frac{1}{2}\cdot\frac{\sigma}{\rho}\left(\frac{x}{v}\right)^2$$

The deflection then shows a linear relation with the deflecting force. Note also that the deflection varies with the square of the distance x, and also inversely as the square of the jet velocity v.

(ii) *Finite deflecting field.*—Considering now Fig. 56, the deflecting field is shown as of finite extent, measured by L, and the jet now leaves its influence at the point Q.

From the preceding result the transverse displacement of the jet at the point Q is

$$y = \frac{1}{2}\cdot\frac{\sigma}{\rho}\left(\frac{L}{v}\right)^2$$

It may be shown also that on reaching Q the jet has a transverse component of velocity given by

$$\frac{\sigma}{\rho}\cdot\frac{L}{v}.$$

Therefore if the jet is allowed to travel a further longitudinal distance B, free from deflecting force, before observation, it will acquire an additional transverse displacement

$$y' = \frac{\sigma}{\rho}\cdot\frac{L}{v}\times\frac{B}{v} = \frac{\sigma LB}{\rho v^2}$$

The total transverse displacement at the point S is then the sum of y and y', or

$$Y = \frac{1}{2}\cdot\frac{\sigma}{\rho}\left(\frac{L}{v}\right)^2 + \frac{\sigma LB}{\sigma v^2}$$
$$= \frac{\sigma}{\rho}\cdot\frac{L}{v^2}\left(\frac{L}{2}+B\right) = \frac{\sigma}{\rho}\cdot\frac{LD}{v^2}$$

where D is the distance from the mid-point of the deflecting field to the screen (see Fig. 56).

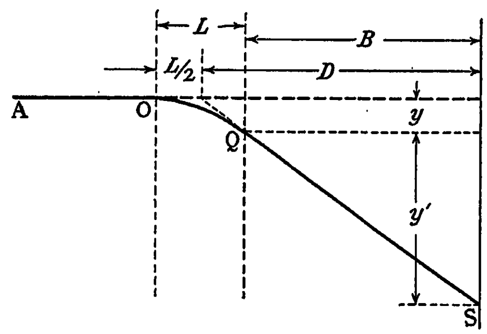


FIG. 56.—Jet passing through a bounded deflecting field.

As before, the deflection is proportional to the deflecting field when the jet velocity is held constant.

(*b*) *Controlled by the jet velocity, with a constant deflecting field.*

It will be noted in the results formulated above that the velocity of the jet is one of the factors controlling the magnitude of the deflection. Owing, however, to the inverse relationship, to preserve a definite deflection it is necessary to maintain a finite velocity of the jet. This condition is secured if the variable quantity is allowed to effect only a change in the velocity, and hence the kinetic energy of the jet (see Section XI, A, 3). The variable then may control a flow of energy (an amount of power) which is added to the normal constant power supplied to the jet.

Thus, if u is the change in the velocity of the jet, we have

$$\text{deflection } Y = \frac{1}{(v+u)^2}\cdot\frac{\sigma}{\rho}LD$$

where u is the applied variable. Similarly the resulting variable, or indicated quantity, is the change in deflection that results, i.e.

$$\begin{aligned}\partial Y &= Y_v - Y_{v+u} \\ &= \frac{1}{v^2}\cdot\frac{\sigma}{\rho}LD - \frac{1}{(v+u)^2}\cdot\frac{\sigma}{\rho}LD \\ &\doteq \frac{\sigma}{\rho}LD\frac{2vu+u^2}{v^2(v+u)^2}\end{aligned}$$

This complicated expression simplifies considerably in the case when u is sufficiently small to be negligible in comparison with v, for then v may be written for $(v+u)$, and u^2 may be neglected, so that

$$\partial Y = 2\frac{\sigma}{\rho}LD\frac{u}{v^3}$$

i.e. it is proportional to the applied variable u, and is also inversely proportional to the cube of the constant component of the jet velocity.

(2) FREQUENCY ERROR.

(*a*) *Deflectional error.*

Referring again to Fig. 56, it will be seen that each element ∂x of the jet is in its turn under the influence of the deflecting field for a finite time interval, the time L/v which the element takes to pass from O to Q. It may be verified from the investigation below that the deflection registered by the jet measures not any instantaneous value of the quantity controlling the deflection (as has been assumed in Section II) but its average value (arithmetic mean, because of the linear law) over the interval of time L/v. But obviously, as long as the fractional variation of the quantity during this time interval is negligible, the deflection may be regarded as measuring the instantaneous value, corresponding for example to the instant when the jet element passes the mid-point of the field. However, this fractional variation may become appreciable, due to the rapidity of variation of the deflecting field as compared with the jet velocity, i.e. the mean value registered by the jet ceases to be equal to the instantaneous value required; the difference is the *frequency error* of the jet.

If the jet element whose deflection is considered passes point O at time t_0, then the deflection is equal to

$$\left\{K\int_{t_0}^{t_0+(L/v)} f(t)\,\partial t\right\} \div \frac{L}{v}\,*$$

the deflecting field being a function of time [i.e. $\sigma = f(t)$], and this is not necessarily equal to the instantaneous value

$$Kf\left(t_0 + \frac{1}{2}\cdot\frac{L}{v}\right)$$

In the first instance assume the case of a sinusoidal periodic quantity, such that

$$\sigma = X\sin(2\pi ft)$$

where f is its frequency.

* Here K is the "calibration constant" of the jet instrument, and from Section XI, A, 1, (*a*) (ii) $K = LD/(\rho v^2)$.

For convenience call $\quad 2\pi ft_0 = \theta$

and
$$2\pi f\frac{1}{2}\cdot\frac{L}{v} = \phi$$

Then the required instantaneous value

$$\begin{aligned}&= X\sin 2\pi f\left(t_0 + \frac{1}{2}\cdot\frac{L}{v}\right) \\ &= X\sin(\theta+\phi)\end{aligned}$$

But the indicated deflection, divided by K, gives

$$\begin{aligned}&\left\{\int_{t_0}^{t_0+(L/v)} X\sin 2\pi ft\,\partial t\right\} \div \frac{L}{v} \\ &= \frac{v}{L}X\frac{1}{2\pi f}\Big[-\cos 2\pi ft\Big]_{t_0}^{t_0+(L/v)} \\ &= \frac{vX}{2\pi fL}\left[-\cos 2\pi f\left(t_0+\frac{L}{v}\right) + \cos(2\pi ft_0)\right] \\ &= \frac{X}{2\phi}\left[-\cos(\theta+2\phi)+\cos\theta\right]\end{aligned}$$

which reduces to

$$\frac{X}{\phi}\sin\phi\sin(\theta+\phi)$$

Thus the ratio of the measured quantity to the true value constitutes a correction factor by use of which allowance may be made for the frequency error.

$$\begin{aligned}\text{This ratio } R &= \frac{\text{indicated value}}{\text{required instantaneous value}} \\ &= \frac{(X/\phi)\sin\phi\sin(\theta+\phi)}{X\sin(\theta+\phi)} \\ &= \frac{\sin\phi}{\phi} \quad\text{or}\quad \frac{v}{\pi fL}\sin\left(\frac{\pi fL}{v}\right)\end{aligned}$$

This relation between R and ϕ is shown in Fig. 57. Notice that R is a periodic function of ϕ, with an amplitude decreasing as ϕ increases, i.e. as the frequency f is progressively increased, or the jet velocity v is progressively decreased, the factor R falls from its initial maximum value unity, passes through zero to a negative maximum (value about $-0{\cdot}22$), swings back through zero to a positive maximum, and so on.

For small values of ϕ it will usually be more convenient to determine the fractional or percentage error; thus

$$\begin{aligned}\text{fractional error } \delta &= 1 - R \\ &= 1 - \frac{\sin\phi}{\phi}\end{aligned}$$

From Fig. 58 we read the following values :—

Percentage error	0·01	0·1	1·0	10
δ	$\frac{1}{10000}$	$\frac{1}{1000}$	$\frac{1}{100}$	$\frac{1}{10}$
$\phi = \frac{\pi fL}{v}$ ..	0·024	0·077	0·246	0·79
$\frac{fL}{v}$ ..	0·00765	0·0245	0·0784	0·252

It will be seen that, up to the highest value shown, the error follows closely a square law with respect to ϕ, the relation being approximately

$$\delta = 0 \cdot 165\phi^2$$

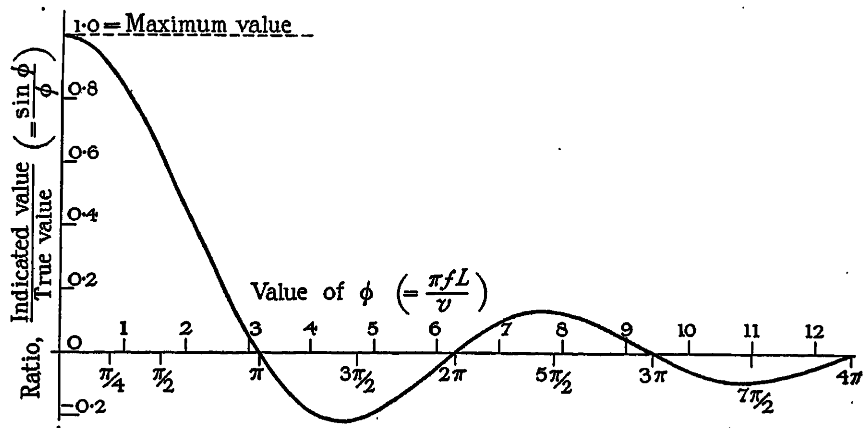


FIG. 57.—High-frequency error of the electrified jet (correction factor R).

When investigating non-periodic and transient quantities, the formulæ given may be applied individually to each sinusoidal component or harmonic present.

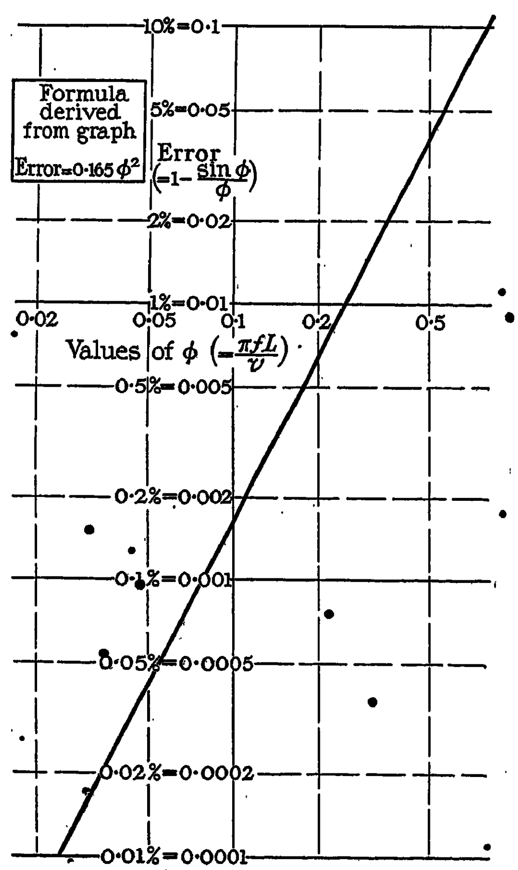


FIG. 58.—High-frequency error of the electrified jet (error δ).

(b) *Phase error.*

In jet cyclographs it commonly happens that the two deflecting fields act on the jet at different parts of its path. The difference in sensitivities, due to the different distances between the two deflecting fields and the recording screen, is easily allowed for in the calibration of the instrument, but a further error arises due to the finite velocity of the jet. If M is the effective distance between the two deflecting fields, then each element of the jet takes a time M/v to pass from one field to the other. As a result this time-lag appears as an error on the cyclogram; with periodic deflecting quantities it may be interpreted as a phase difference; and with sinusoidal quantities as a phase angle, α; then

$$\frac{M}{v} = \frac{\alpha}{2\pi}T, \quad \text{or} \quad \frac{M}{v} = \frac{\alpha}{2\pi f}$$

where T is the time period and f the frequency of the periodic quantity. Thus

$$\alpha = \frac{M}{v} \times 2\pi f$$

This error may be allowed for by taking a second cyclogram with the positions of the deflecting fields interchanged. This second cyclogram must be corrected for the differing sensitivities, so that each quantity preserves the same calibration constant for the two cyclograms. The two cyclograms are then correctly superimposed, i.e. with corresponding axes coinciding in both direction and sense; then since the error in the second cyclogram is of the same magnitude as, but opposite in sign to, that in the first, a mean curve between the two will give the correct time relation between the two periodic quantities.

(3) POWER IN THE JET.

Each element of length ∂x of the jet has a mass $\rho\partial x$ and travels with a velocity v; it therefore possesses an amount of kinetic energy $\frac{1}{2} \times \rho\partial x \times v^2$.

The time taken by such an element to pass a fixed point is $\partial x/v$. Hence the number of elements passing

such a point in unit time is $v/\partial x$ and the total energy of these is

$$\{\tfrac{1}{2} \times \rho\partial x \times v^2\} \times \frac{v}{\partial x}$$
$$= \tfrac{1}{2}\rho v^3$$

which is the power flowing past the fixed point and carried by the jet (note that it is proportional to the *cube* of the velocity).

(B) The Electron Jet.

(1) Physical constants of the electron.

The electron carries an electric charge or quantity of electricity which, having so far proved to be indivisible, may be regarded as the "atom" of electricity. Its value is

$4 \cdot 77 \times 10^{-10}$ electrostatic units
$1 \cdot 59 \times 10^{-20}$ electromagnetic units
or $1 \cdot 59 \times 10^{-19}$ coulombs

When in motion the electron behaves as though it possessed mechanical inertia, which for low velocities of motion (compared with the velocity of light) remains constant at the value

$$8 \cdot 96 \times 10^{-28} \text{ gramme}$$

It is perhaps more strictly accurate not to call this quantity "mass," but to define it as the ratio of a force which may be applied to the particle, to the linear acceleration of the particle caused by the applied force —for it is found that when the electron moves with velocities in the neighbourhood of that of light this ratio increases in value.

Lorentz, Abraham and others have suggested explanations of this phenomenon, and have deduced formulæ depicting the relation between inertia and velocity. Jones * has shown recently, however, that the formulæ of Lorentz more nearly fit his experimental results on cathode rays, and accordingly these formulæ are used here. They show that the increase of the inertia of the electron is greater for forces acting parallel with the velocity (longitudinal forces) than for forces acting perpendicular to the velocity (transverse forces), the ratios of increase being as follows :—

For longitudinal forces, $m_l/m_0 = (1-\beta^2)^{-3/2}$
and for transverse forces, $m_l/m_0 = (1-\beta^2)^{-1/2}$

where β is the ratio of the electron velocity to the velocity of light.

It will be discovered in a succeeding Section (XI, B, 3) that the determining factor in the response of an electron to a deflecting force is the ratio of its charge to its inertia; the value for low velocities is

$1 \cdot 77 \times 10^7$ C.G.S. (electromagnetic) units per gramme
or
$1 \cdot 77 \times 10^6$ coulombs/gramme.

It is this extremely high value that renders the electron so useful in jet-measuring instruments, since it enables reasonable sensitivity to deflection to be obtained in spite of the very high velocities of the electrons in cathode rays (ranging from 1/30th to 1/3rd of the velocity of light).

* See Bibliography, (125).

(2) Energy relations of the electron jet.

(*a*) *Velocity.*

An electron immersed in an electric field whose strength is X, experiences a force Xe in the direction of the field (but, with the accepted convention of signs, in the *opposite sense,* due to the charge e on the electron being negative). In the absence of constraint, therefore, the electron moves, and for each element ∂x of its path it acquires energy by an amount $Xe\partial x$; hence if it starts from rest and moves a distance x without resistance its total kinetic energy becomes

$$W = \int_0^x Xe\partial x = e\int_0^x X\partial x$$

But $\int_0^x X\partial x$ is the potential difference E over the distance x, hence

$$W_x = eE$$

Now $W_x = \tfrac{1}{2}m_l v^2$, m_l being the inertia of the electron in the direction of the acquired velocity,

whence $v^2 = Ee \div \tfrac{1}{2}m_l$

and $v = \sqrt{\left(\frac{2Ee}{m_l}\right)}$

The velocity then is proportional to the square root of the accelerating P.D., as long as the inertia remains sensibly constant. The exact relation is shown in Fig. 59.

(*b*) *Power.*

If ν is the linear density of electrons in the jet, then the rate of flow of electrons is νv. But each carries an amount of energy $W = \tfrac{1}{2}m_l v^2$, therefore the rate of flow of energy, or power carried by the jet, is the product

$$\tfrac{1}{2}m_l\nu v^3$$

As in the general case (Section XI, A, 3), this is proportional to the *cube* of the velocity.

Alternatively, however, $W = eE$, giving power in jet

$$= eE \times \nu v$$

Now $\nu v \times e$ is the rate of flow of charge, i.e. the current I carried by the jet, whence

$$\text{power} = EI$$

(3) Deflection of the electron jet.

(*a*) *Field control.*

(i) *By an electric field.*—In an electron jet which is under the influence of an electrostatic deflecting field whose component perpendicular to the jet has the value X, the transverse acceleration of the jet is that

of its component particles, and from the preceding Section this is

$$f_t = \frac{Xe}{m_t}$$

m_t being the inertia of the electron in a direction perpendicular to the jet velocity.

From Section XI, A, 1, (*a*), (ii), the deflection registered by the jet on the screen is

$$Ye = f_t\frac{LD}{v^2}$$

$$= \frac{XeLD}{m_tv^2}\left[= \frac{Xe\sqrt{\{1-(v^2/c^2)\}}}{m_0v^2}LD\right]$$

The deflection varies inversely as the *square* of the jet velocity.

(ii) *By a magnetic field.*—If the jet is immersed in a magnetic field whose component perpendicular to the jet is H, the force acting on the element ∂x is given by

$$H\partial xI = H\partial x\,.\,vev$$

But the inertia of this element of the jet to transverse forces is $\nu\partial x\,.\,m_t$, since there are $\nu\partial x$ electrons contained in the element; its transverse acceleration will therefore be

$$f_t = H\partial x\,.\,vev \div \nu\partial x\,.\,m_t$$

$$= \frac{Hev}{m_t}$$

As before, the deflection registered by the jet is

$$Y_m = f_t\frac{LD}{v^2}$$

$$= \frac{HeLD}{m_tv}\left[= \frac{He\sqrt{\{(1-(v^2/c^2)\}}}{m_0v}LD\right]$$

Note that in this case the deflection varies inversely as the *first power* of the jet velocity.

(iii) *Specific sensitivity.*—In an actual electron-jet instrument, the lengths L and D, and the value of the deflecting field for a unit applied electrical quantity, depend upon the construction of the instrument. Hence the value of the jet as a measuring device in any particular instrument is found by eliminating these factors from the measured sensitivity of the instrument—the result, which may be called the "specific sensitivity" of the jet, for deflection by an electric field is

$$Y_e \div XLD = \frac{e}{m_tv^2}$$

and similarly for a magnetic field it is

$$Y_m \div HLD = \frac{e}{m_tv}$$

In the case of an electron jet, therefore, the relation

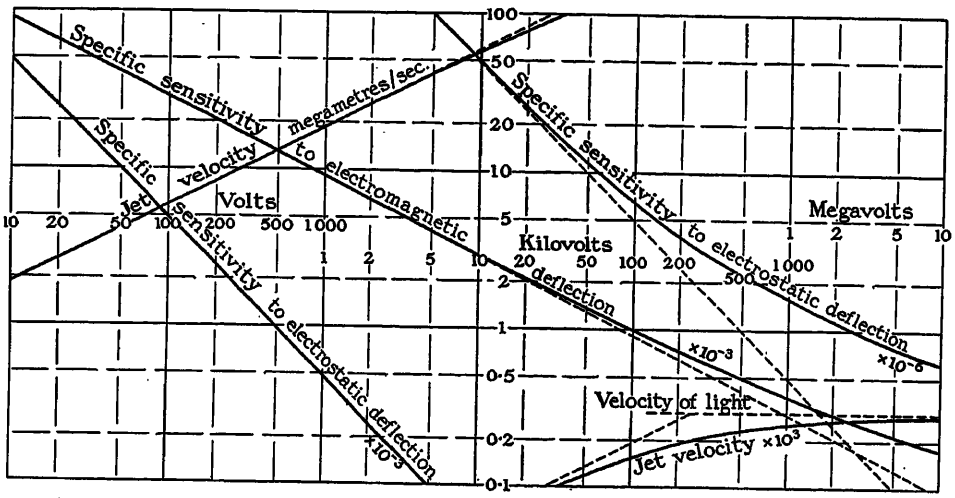


FIG. 59.—Properties of the electron jet.

between the specific sensitivity and the velocity of the jet is more complex than in the general case. Fig. 59 enables the relation to be determined.

Nevertheless, over the range for which the electron inertia (m_t) may be regarded as constant, the specific sensitivity varies inversely as the square of the jet velocity for electric deflection, and inversely as the first power for magnetic deflection. Thus a high-velocity jet is relatively more sensitive to magnetic deflection, and a low-velocity jet relatively more sensitive to electric deflection.

(*b*) *Velocity control.*

(i) *With constant electric field.*—As in the general case [see Section XI, A, 1, (*b*)] the deflection of the electron jet may be controlled by its velocity, the jet passing through a constant deflecting field, equally as well as by a variable field acting on a constant velocity jet.

If the constant field is an electrostatic one, the deflection (from the preceding Section) is

$$Y_v = \frac{XeLD}{m_tv^2}$$

and when the variable component u is added to the velocity the deflection is

$$Y_{v+u} = \frac{XeLD}{m_t(v+u)^2}$$

The useful indication of the instrument is therefore the difference, which was found to be

$$\partial Y = \frac{XeLD}{m_t} \cdot \frac{2vu + u^2}{v^2(v+u)^2}$$

In circular oscillograms, more especially with a high ratio between the frequency of the applied periodic quantity and the speed of rotation of the time scale, it is possible to work with ∂Y small compared with Y; this means that u is small compared with v, and renders possible a simplification of the above expression, which in turn simplifies the calibration of the instrument.

Then in the limit when u/v is negligible, ∂Y becomes

$$\partial Y = 2\frac{XeLD}{m_t} \cdot \frac{u}{v^3}$$

i.e. a linear law holds between the indication and the applied quantity.

It may be mentioned here that it is desirable to keep u relatively small when a high-velocity jet is used, to minimize errors due to the change of inertia (and hence in deflectional sensitivity) with change of velocity.

(ii) *With constant magnetic field.*—When the field used is a magnetic one, the expression for the deflection is

$$Y_v = \frac{HeLD}{m_t v}$$

and similarly $$Y_{v+u} = \frac{HeLD}{m_t(v+u)}$$

whence the useful indication is

$$\partial Y = \frac{HeLD}{m_t} \cdot \frac{u}{v(v+u)}$$

and when u is negligible compared with v, this reduces to

$$\partial Y = \frac{HeLD}{m_t} \cdot \frac{u}{v^2}$$

i.e. the linear law holds just as in the previous case.

(4) FREQUENCY ERROR.

(*a*) *Deflectional error.*

In Section XI, A, 2, (*a*) it has been determined that for errors up to 10 per cent at least, the frequency error δ for an electrified jet (expressed as a fraction of the true value) follows closely the relation

$$\delta = 0{\cdot}165\left(\frac{\pi f L}{v}\right)^2$$

This formula applies without modification to the electron jet, though it is more convenient to transpose it into the form

$$\left(\frac{fL}{v}\right)^2 = \delta \div 0{\cdot}165\pi^2$$

or $$f = \frac{v}{L} \times 0{\cdot}783\sqrt{\delta}$$

where f is the frequency limit for a specified error δ of an instrument wherein L and v are known.

(*b*) *Phase error.*

Similarly, from Section XI, A, 2, (*b*), the phase error

$$a = \frac{2\pi f M}{v}$$

and this formula also applies directly to the electron jet. Transposing, we have

$$f = \frac{v}{M} \cdot \frac{a}{2\pi}$$

Note that $a/(2\pi)$ is the phase error expressed as a fraction of a cycle.

(5) "SCATTERING" OF THE ELECTRON JET.

(*a*) *The dispersive force.*

It has been noted (Section VI) that one of the causes of the scattering of the electron jet is the inherent mutual repulsion between the electrons composing the jet, and it is proposed here to investigate the forces causing such motion and hence determine the relative importance of the effect.

Assume an electron jet whose initial condition is an exactly parallel motion of its electrons, their velocity being constant and equal to v cm per sec. Further assume that the jet is circular in cross-section and that initially there is uniform distribution of the electrons over the whole cross-section.

In Figs. 60 and 61 is shown a cross-section of the jet; the circle ACBD represents the boundary of the jet, of radius R cm and centre P. Let O be any electron within the jet, the force on which it is required to determine; define its position by its distance from the jet axis, x = PO.

By symmetry it will be seen that the forces exerted on the electron O by the electrons within the segment ADBO are neutralized by the forces of those in the portion AEBO; this portion is a segment of a circle also of radius R, whose centre is Q, such that PD = EQ = R.

It is necessary to consider therefore only the part of the jet AEBC; the force on the electron O due to this is radially outwards along the direction OQ. Suppose this part to be divided into a large number of elementary longitudinal filaments, each of cross-sectional area dA, where A is the cross-sectional area of the whole jet ($A = \pi R^2$).

If ν is the linear density of electrons in the whole jet, then $(\partial A/A)\nu$ is the linear density of electrons in each filament, and the linear density of charge is $(\partial A/A)\nu e$.

TABLE 9.

Recording Power of Some Electron Jets.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
			Instrument		Jet constants				Indication				Record		
													Periodic	Transient	
Ref. No.	Authority	Date	Maker	Type of cathode	Current	P.D.	Velocity	Power	Diameter of "spot"	Form	Length	Area	Power density	Duration	Energy density
					μA	kV	cm/sec.	mW	cm		cm	cm²	watt/cm²	sec.	joule/cm²
89	Dufour, A.	1922	(Own)	Cold	(10)	60	$12 \cdot 6 \times 10^9$	600	0·1	One wave	3	0·3	—	1×10^{-7}	$0 \cdot 2 \times 10^{-6}$
101	Johnson, J. B. . .	1922	W. E. Co.	Hot	(20)	0·3	$1 \cdot 04 \times 10^9$	6	(0·1)	(Ellipse)	(10)	(1)	6×10^{-3}	—	—
115	Watson Watt, R. A.	1923	W. E. Co.	Hot	(20)	0·4	$1 \cdot 3 \times 10^9$	8	(0·1)	Waves	(10)	(1)	—	1×10^{-3}	8×10^{-6}

TABLE 10.*

Sensitivities of Some Electron Jets.

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			Instrument		Jet		Sensitivity data						
							Electrostatic deflection					Instrument sensitivity	
Ref. No.	Authority	Date	Maker	Type of cathode	P.D.	Velocity	L_e	S_e	D_e	$\frac{L_e D_e}{S_e}$	Specific sensitivity from Fig. 59	Calculated	Measured
					kV	cm/sec.	cm	cm	cm	cm		cm/volt	cm/volt
90	Hull, L. M. . .	1921	(Own)	Cold	10	$5 \cdot 8 \times 10^9$	10	1·5	(35)	233	49×10^{-6}	0·0114	0·011
90	Hull, L. M. . .	1921	(Own)	Hot	0·5	$1 \cdot 33 \times 10^9$	10	1·5	(35)	233	1×10^{-3}	0·233	0·25
97	Keys, D. A. . .	1922	(Own)	Hot	5	$4 \cdot 15 \times 10^9$	5	0·5	(15)	150	$0 \cdot 1 \times 10^{-3}$	0·015	0·02
101	Johnson, J. B.	1922	W. E. Co.	Hot	0·25	$1 \cdot 05 \times 10^9$	1·37	0·47	(17)	49·5	2×10^{-3}	0·099	0·1
89	Dufour, A. . .	1922	(Own)	Cold	30	$9 \cdot 6 \times 10^9$	8	0·5	(50)	800	18×10^{-6}	0·0144	0·01

* Extracted from a Report to the British Electrical and Allied Industries Research Association.

It may be shown that the force exerted on electron O by the whole filament is

$$2\frac{e^2\nu}{r\kappa}\cdot\frac{\partial A}{A}$$

where r is the distance of the fialment from O, and the required radial component is

$$\frac{2e^2\nu\partial A}{r\kappa\,.\,A}\cos\theta=\frac{2e^2\nu}{\kappa A}\cos\theta\partial\theta\partial r$$

since $\partial A=\partial r\times r\partial\theta$.

The radial force due to the elementary sector KM is obtained by integrating this expression with respect to r between the limits $r_1 = \text{OK}$ and $r_2 = \text{OM}$. The result is

$$\frac{4e^2\nu x}{xA}\cos^2\theta\partial\theta$$

Similarly by integrating with respect to θ between the limits $-\frac{1}{2}\pi$ and $+\frac{1}{2}\pi$ (corresponding to the points A and B) the total radial force is obtained :—

$$\frac{4e^2\gamma x}{\kappa A}\cdot\frac{\pi}{2}=\frac{2e^2\nu}{\kappa}\cdot\frac{x}{R^2}$$

since $A=\pi R^2$.

Note that at any instant the force acting on any electron is proportional to x, its distance from the centre of the jet; electrons at the centre therefore experience no force, as would be expected from symmetry.

Secondly, if the distribution of electrons over the cross-section of the jet remains uniform while the jet is expanding, each electron must maintain its relative position in the jet, i.e. $x/R=\gamma$ is constant; hence the force on it is

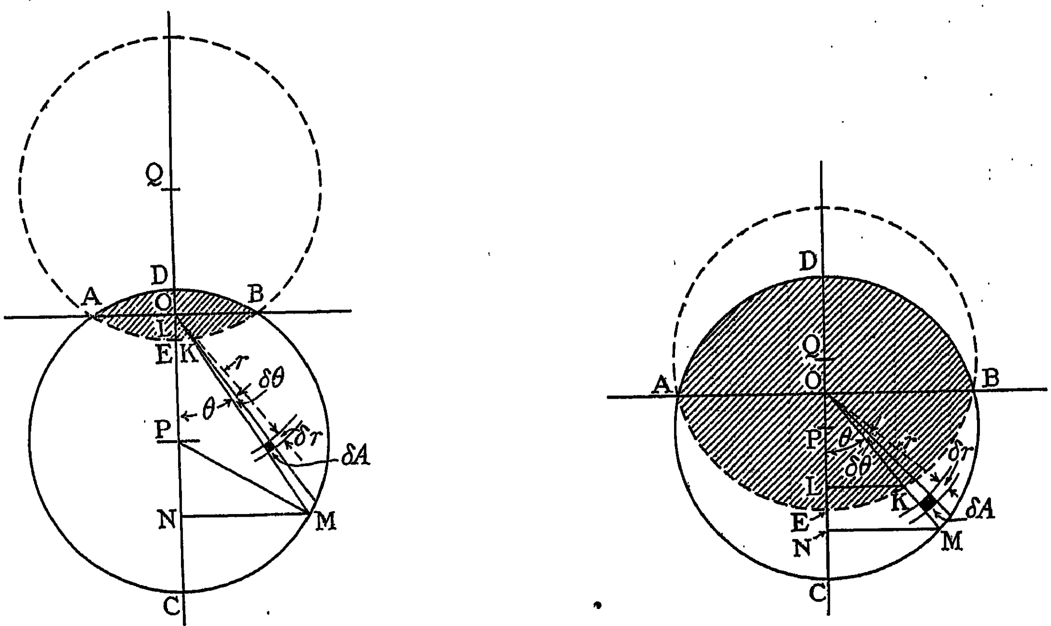
$$\frac{2e^2\nu}{\kappa}\gamma\frac{1}{R}$$

i.e. the "dispersing force" is inversely proportional to the size of the jet.

Now if I is the current in the jet, and Δ is the current density (which has been assumed uniform), we have

$$I=\nu e v$$
$$=\Delta\pi R^2$$

giving
$$\nu=\frac{I}{ev}=\frac{\Delta\pi R^2}{ev}$$



FIGS. 60 and 61.—Cross-section of jet.

Thus the dispersive force may alternatively be written

$$\frac{2e}{\kappa v}\cdot\frac{\gamma I}{R}$$

or
$$\frac{2\pi e}{\kappa v}\gamma\Delta R$$

(b) *The dispersion of the jet.*

The radial displacement of any electron after a small time interval is proportional to its acceleration and hence the force acting on it, since it starts from rest (the jet being assumed initially parallel). This displacement then is proportional to the radius, and as a result of this the electron maintains its relative position in the jet. Initially, therefore, the distribution of electrons throughout the cross-section of the jet tends to remain uniform during its expansion.

Assume that this condition holds for a ratio of expansion x, such that $R_t = xR_0$, where R_0 is the initial radius of the jet and R_t its radius after a time t

TABLE 11.

High-Frequency Error of Some Electron Jets.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Ref. No.	Authority	Date	Instrument		Jet		Frequency error									
							Deflectional					Phase				
			Maker	Type of cathode	P.D.	Velocity, v	L_e	$\frac{L_e}{v}$	Frequency f for error δ = 0·0001	0·01	1·0	M_e	$\frac{M_e}{v}$	Frequency f for error α = 0·9°	9°	90°
					kV	cm/sec.	cm	sec.				cm	sec.			
96	Samson, C. . . .	1918	—	Hot	9	$5·53\times10^9$	6	$1·09\times10^{-9}$	$7·2\times10^6$	72×10^6	$0·72\times10^9$	—	—	—	—	—
90	Hull, L. M. . . .	1921	(Own)	Cold	10	$5·8\times10^9$	10	$1·73\times10^{-9}$	$4·52\times10^6$	$45·2\times10^6$	$0·452\times10^9$	—	—	—	—	—
90	Hull, L. M. . . .	1921	(Own)	Hot	0·5	$1·33\times10^9$	10	$7·5\times10^{-9}$	$1·04\times10^6$	$10·4\times10^6$	$0·104\times10^9$	—	—	—	—	—
101	Johnson, J. B. . . .	1922	W. E. Co.	Hot	0·3	$1·04\times10^9$	1·37	$1·32\times10^{-9}$	$5·93\times10^6$	$59·3\times10^6$	$0·593\times10^9$	(2)	$1·92\times10^{-9}$	$1·3\times10^6$	13×10^6	$0·13\times10^9$
89	Dufour, A. . . .	1922	(Own)	Cold	30	$9·56\times10^2$	8	$0·837\times10^{-9}$	$9·35\times10^6$	$93·5\times10^6$	$0·935\times10^9$	—	—	—	—	—
97	Keys, D. A. . . .	1922	(Own)	Hot	5	$4·15\times10^9$	5	$1·2\times10^{-9}$	$6·5\times10^6$	65×10^6	$0·65\times10^9$	—	—	—	—	—
92	Wood, A. B. . .	1923	(Own)	Hot	3	$2·21\times10^9$	9	$2·8\times10^{-9}$	$2·8\times10^6$	28×10^6	$0·28\times10^9$	—	—	—	—	—

(measured from its parallel start). Then the law connecting the force on an electron with its radius remains true, and, for the bounding electrons of the jet,

$$\text{Force} = \frac{2e^2\nu}{\kappa}\cdot\frac{1}{R_0x} \quad (\text{since } \gamma = 1)$$

Now the acceleration of each of these electrons is

$$\frac{d^2}{dt^2}R_t = R_0\frac{d^2x}{dt^2}$$

Then
$$m_tR_0\frac{d^2x}{dt^2} = \frac{2e^2\nu}{\kappa}\cdot\frac{1}{R_0x}$$

or
$$x\frac{d^2x}{dt^2} = \frac{2e^2\nu}{\kappa m_tR_0^2}$$

This equation gives the required relation between the expansion ratio x and the time t.

On substitution of the radial velocity $(d/dt)R_t$ of the bounding electron the equation becomes of the

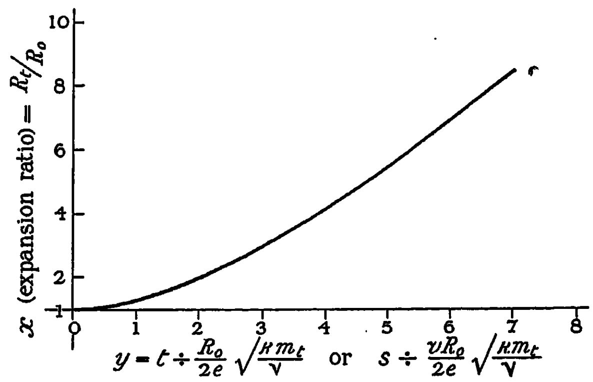


FIG. 62.—Scattering of an electron jet.

first order, and on subsequent integration it reduces to the form

$$t = \frac{R_0}{2e}\sqrt{\left(\frac{\kappa m_t}{\nu}\right)}\int\frac{1}{\sqrt{(\log_e x)}}\partial x$$

From this equation was obtained the relation between x and t shown by the curve (Fig. 62).

Now since the jet has a constant velocity v, we have $s = vt$, so that the equation may be written

$$s = \frac{vR_0}{2e}\sqrt{\left(\frac{\kappa m_t}{\nu}\right)}\int\frac{1}{\sqrt{\log_e x}}\partial x$$

where s is the distance travelled in time t, and therefore measures the position along the jet at which the expansion ratio is x. The curve therefore gives the relation between x and s, i.e. the shape of the jet.

(c) Characteristics of the phenomenon.

An inspection of the curve (Fig. 62) shows that it commences as a parabola and then tends to become a straight line; this leads to two useful results, which may also be deduced from the formulæ :—

(i) At the commencement of the jet's motion the radial velocity of the electrons is zero; hence their radius (position) and so their acceleration may be

assumed constant, under which condition their displacement (measured by $x - 1$) is proportional to the square of the time t and the distance s.

(ii) In the limit when R_t is large compared with R_0, the force and hence the radial acceleration of the electrons tends to zero, hence their radial velocity may be assumed constant; the displacement therefore becomes a linear function of the time t and distance s.

More important, perhaps, are other properties that are suggested by the formulæ :—

By substituting as, in Section (*a*) the alternative expressions for the linear electron density,

$$\nu = \frac{I}{ev} = \frac{\Delta_0 \pi R_0^2}{ev}$$

the constant in the equation takes the forms

$$\frac{R_0}{2}\sqrt{\left(\frac{v^3}{I} \cdot \frac{\kappa m_t}{e}\right)}$$

and

$$\frac{1}{2}\sqrt{\left(\frac{v^3}{\Delta_0} \cdot \frac{\kappa m_t}{\pi e}\right)}$$

(iii) If therefore the current density Δ_0 and the velocity v are kept constant, as may be achieved in a cold-cathode instrument by maintaining constant discharge conditions, the distance s travelled by the jet before a given ratio of expansion x occurs is independent of variations in the initial diameter $2R_0$ (controlled by the size of the diaphragm hole).

(iv) If, however, the current is made constant, the velocity v also remaining constant, the time t and the distance s taken to reach a given fractional expansion x are proportional to the initial diameter ($2R_0$) of the jet, i.e. *the smaller the jet, the faster it grows.*

(v) If the initial diameter is constant but the current in the jet is varied, the time t and the distance s for a given value of x vary inversely as the square root of the current I, i.e. *the more intense the jet, the faster it grows.*

(vi) With the initial diameter and the current held constant, the time t for a given x varies directly as the square root of the velocity v; but the distance s varies as the 3/2 power of the velocity, i.e. *the slower the jet, the faster it grows.*

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THE ELECTRICAL CONDUCTIVITY OF CERTAIN LIGHT ALUMINIUM ALLOYS AND COPPER CONDUCTORS AS AFFECTED BY ATMOSPHERIC EXPOSURE.*

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(*Paper first received* 21*st April, and in final form* 20*th July*, 1925.)

SUMMARY.

The paper deals primarily with the effect which atmospheric exposure has upon the electrical conductivity of certain light aluminium alloys, the period of exposure extending to 24 years. Twenty-five alloys of aluminium with the metals copper, nickel, manganese and zinc in amounts not exceeding 1 or 2 per cent have been tested at intervals for electrical resistance, whence the variation in conductivity has been found. In the case of copper alone, or copper and manganese jointly, the conductivity continuously diminishes in value, whereas with copper and nickel, or copper and zinc, or combinations of all three of these, the conductivity at first decreases, and then in some cases increases in a remarkable manner, finally attaining a more or less constant value. The factors concerned are the specific resistance of the alloy and the loss of metal due to corrosion, and it has been found possible to separate the total variation into these two classes. Some further work deals with the exposure of copper conductors.

This paper brings together the results of a series of exposure tests of certain light aluminium alloys and copper conductors which have been in progress since 1901, and which have been reported upon from time to time at meetings of the British Association.† The physical properties of the aluminium alloys were dealt with in a paper read before the Institution,‡ to which reference should be made for further details. All the specimens are in the form of wire 0·126 inch (3·2 mm) diameter, and have been exposed on the roof of King's College, London. In Table 1, which is taken from the Institution paper, will be found the composition and certain other data relating to the alloys before exposure. The tests to be now considered consisted in measuring the electrical resistance of each wire in the months of July or August in any one year, and reducing the resistance to 15° C. by aid of the temperature coefficient given in Table 1, the assumption being that the coefficient has remained constant.

A specimen of each alloy has been preserved in a box in the Laboratory, and the variation of specific resistance of certain of these specimens is given in Table 2. All these specimens are bright, with the exception of one or two which are very slightly clouded, and they are all in good condition. None of them was annealed, as was the case in certain of the exposed wires.

Let R_0 be the electrical resistance, ρ_0 the specific resistance, and r_0 the radius of the wire before exposure, and let R_t, ρ_t, r_t be the same quantities at time t during exposure. Then $\pi r_t^2/\rho_t = (\pi r_0^2/\rho_0)(R_0/R_t)$. In the graphs the values of R_0/R_t are plotted against the time of exposure t in years. The variations in the ordinate are due to variations in the ratio of the effective conducting area to the effective specific resistance. In the case of an unevenly corroded wire the radius r has no very obvious meaning, and it does not follow that the specific resistance has a constant value over the conducting cross-section.

It should be noted that all the specimens of Table 1 were raised to about 100° C. in an oil bath during the determination of the temperature coefficient; in addition, specimens 12 to 24 inclusive were annealed before exposure at a temperature of 435° C. The consequent increase in conductivity varied by small amounts to 3·8 per cent in the case of alloy 22. In the paper the conductors are grouped according to the elements added to the aluminium.

Further tests have been made to separate the effects due to loss of metal by corrosion from those due to variation of specific resistance. The initial volume of unit length of the conductor is $\pi r_0^2 = a_0$, say, and the volume of the corroded portion of unit length at time t is the weight of the metal lost divided by its specific gravity, equal to b_t, say. Then the ratio

$$\frac{R_t}{R_0} = \frac{\rho}{\rho_0} \times \frac{a_0}{a_0 - b_t}$$

where the first term deals with the increase in resistance due to variation of specific resistance, and the second term deals with the increase due to diminution of volume. Care was taken when removing the corroded portion not to go beyond the point at which the electrical resistance of the conductor would be increased. The resistance of a known length of the conductor and its weight were then determined. With this information and the other known data the figures given in Table 4 have been worked out, and the last two columns give the calculated and observed values of the ratio R_t/R_0.

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† *Report of the British Association for the Advancement of Science*, 1901, p. 771; 1902, p. 734; 1903, p. 777; 1904, p. 686; 1908, p. 827; 1911, p. 480; 1912, p. 570; 1913, p. 606; 1915, p. 647; also *Engineering*, 1901, vol. 72, p. 464; *Electrician*, 1902, vol. 49, p. 868; 1903, vol. 51, p. 898; 1904, vol. 53, p. 752; 1908, vol. 61, p. 837; 1911, vol. 67, p. 907; 1912, vol. 69, p. 945; 1915, vol. 75, p. 886; and *Journal of the Royal Society of Arts*, 1901–2, vol. 50, p. 54.

‡ *Journal I.E.E.*, 1902, vol. 31, p. 321.

TABLE 1.

Group	No. of Specimen	Analysis: Si	Fe	Cu	Ni	Mn	Zn	Al	Specific resistance in microhms/cm³ at 15° C.	Specific resistance at 15° C. after annealing for ½ hour at 435° C. and cooling in air	Average temp. coefficient per deg. C. between following limits of temperature: 0° C. and 50° C.	0° C. and 100° C.	Percentage extension with 10 250 lb./sq.in. of cross-section	Limit of elasticity in lb./sq. in. of cross-section	Breaking load in lb./sq. in. of cross-section	Average linear coefficient of expansion per deg. C. between 16° C. and 100° C.	Spec. gravity before annealing
I	25	0·14	0·31	—	—	—	—	99·55	2·773	—	—	0·00393	0·190	19 376	28 200	0·0000234	2·715
II	16	0·31	0·37	0·11	—	—	—	99·21	2·92	2·83	0·00354	0·00318	0·177	19 500	26 600	0·0000236	2·719
	4	0·38	0·25	0·16	—	—	—	99·21	2·88	—	0·00341	0·00324	0·200	17 900	25 700	0·0000234	2·748
	13	0·38	0·25	1·58	—	—	—	97·79	3·34	3·30	0·00295	0·00283	0·194	32 500	39 000	0·0000239	2·748
	14	0·40	0·31	1·86	—	—	—	97·43	3·25	3·18	0·00302	0·00303	0·183	32 500	40 600	0·0000240	2·748
	15	0·40	0·40	2·61	—	—	—	96·59	3·34	3·26	0·00311	0·00296	0·186	34 500	43 500	0·0000241	2·764
	24	0·35	1·16	0·09	—	—	—	98·40	2·97	2·955	0·00365	0·00357	0·194	20 300	31 300	0·0000248	2·731
III	7	0·37	0·25	0·05	0·75	—	—	98·58	3·05	—	0·00328	0·00320	0·189	20 300	29 700	0·0000246	2·723
	8	0·35	0·29	0·09	1·19	—	—	98·08	3·24	—	0·00337	0·00320	0·237	23 600	33 700	0·0000236	2·731
	20	0·37	1·10	0·06	2·25	—	—	96·22	3·18	3·14	0·00335	0·00329	0·189	20 300	38 600	0·0000234	2·756
	21	0·39	2·57	0·10	1·39	—	—	95·55	3·24	3·195	0·00352	0·00320	0·194	24 400	42 200	0·0000222	2·770
	22	0·37	0·43	1·08	1·29	—	—	96·83	3·41	3·28	0·00173	0·00178	0·146	36 600	45 900	0·0000252	2·747
IV	10	0·32	0·54	0·02	—	0·05	—	99·07	3·09	—	0·00322	0·00311	0·191	22 700	29 200	0·0000222	2·722
	9	0·31	0·35	0·03	—	0·35	—	98·96	3·30	—	0·00311	0·00291	0·183	22 300	30 500	0·0000231	2·733
	23	0·44	0·56	0·09	—	1·78	—	97·13	3·49	3·35	0·00273	0·00245	0·186	24 400	35 300	0·0000230	2·750
V	1	0·38	0·22	0·17	—	—	0·62	98·61	2·86	—	0·00369	0·00357	0·286	23 600	28 100	0·0000245	2·720
	2	0·43	0·28	0·30	—	—	1·20	97·79	2·94	—	0·00346	0·00320	0·171	20 300	30 500	0·0000241	2·728
	5	0·43	0·39	0·09	—	—	2·04	97·05	3·07	—	0·00319	0·00325	0·171	20 700	26 000	0·0000230	2·749
	3	0·37	0·28	0·59	—	—	0·59	98·17	3·06	—	0·00327	0·00306	0·180	22 300	30 500	0·0000227	2·732
	6	0·39	0·31	0·63	—	—	1·20	97·47	3·12	—	0·00324	0·00316	0·237	24 400	30 900	0·0000244	2·742
VI	17	0·35	0·53	0·10	0·83	—	0·90	97·27	3·03	3·005	0·00324	0·00320	0·191	18 300	31 700	0·0000236	2·751
	12	0·31	0 59	0·19	1·09	—	0·73	97·09	3·33	3·18	0·00330	0·00318	0·197	21 500	31 700	0·0000236	2·738
	18	0·43	0·40	0·21	1·13	—	1·94	95·89	3·24	3·245	0·00332	0·00319	0·189	22 300	34 500	0·0000245	2·763
	19	0·35	0·29	0·11	2·01	—	1·77	95·47	3·26	3·205	0·00263	0·00238	0·160	20 300	36 200	0·0000225	2·770
	11	0·39	0·56	0·24	2·31	—	0·38	96·12	3·48	—	0·00308	0·00300	0·194	24 400	34 500	0·0000235	2·741

(I) Commercial Aluminium.

Specimen 25, described as "commercial aluminium," contains 99·55 per cent of aluminium and in this respect would appear to correspond to the quality of aluminium now normally supplied for electrical conductors. The term "commercial aluminium" now has a particular significance in the aluminium industry and signifies a metal of somewhat lower purity, such as is normally used for general purposes. Metal for electrical purposes, having a purity of 99·5 per cent of aluminium and over, is no longer described as "commercial aluminium."

Table 2.

Alloy	Specific resistance at 15° C. 1901	1925	Difference
	microhms per cm³		per cent
4 unannealed	2·88	2·893	+ 0·45
8 unannealed	3·24	3·161	− 2·44
22 unannealed	3·41	3·306	− 3·05
23 unannealed	3·49	3·420	− 2·01
25 unannealed	2·773	2·773	nil

It is interesting to compare the properties of specimen 25 with those of the present-day wires supplied for electrical purposes, as given in the recently issued British Standard Specification No. 215. The following table summarizes the differences for wires of 0·126 inch diameter:—

	Specimen 25, 1901	B.E.S.A. Standard, 1925
Tensile strength	28 200 lb./sq. in.	26 000 lb./sq. in.
Elongation	1·86 per cent (on 13·8 in.)	2·0 per cent (on 10 in.)
Specific resistance at 60° F.	2·7795 microhms/cm³	2·8056 microhms/cm³
Specific gravity	2·715	2·705

The chief difference lies in the low value of the specific resistance, which is all the more remarkable in that the tensile strength of specimen 25 is higher than that of the present-day standard. Using the formula given in the British Standard Specification connecting the specific resistance R with the tensile strength T_p, viz.

$$R = 2 \cdot 7320 + 2 \cdot 8289 \times 10^{-6} T_p$$

the specific resistance of the specimen should be 2·8112 microhms/cm³ at 60° F., as against the actual value of 2·7795. The latter therefore appears low, but it was confirmed by tests made at the National Physical Laboratory at the time, under the date 9th July, 1902. This figure is fractionally higher than the one given in the Institution paper, which was obtained from another portion of the same wire. It would appear, therefore, that though apparently comparable as regards purity, specimen 25 differs in important respects from present-day electrical wires.

Although not properly coming under the copper-aluminium group the curve obtained (25) for this specimen is plotted in Fig. 1. Another specimen (25A) from the same coil and first exposed in 1911 has diminished in conductivity at about the same rate, and has slightly increased in conductivity during the rest of six years in the Laboratory (Table 3).

Referring to Table 4 it will be seen that the specific resistance of specimens 25A and 25 has increased, and that the increase in resistance is largely due to loss of metal. Great care was taken to establish the recorded increase in specific resistance, and a second piece of 25A was tested and gave a value of $2 \cdot 914 \times 10^{-6}$ at 15° C. The unexposed specimen (25) which has been preserved in the Laboratory shows no alteration in specific resistance (Table 2). On removing the corroded portion the metal is perfectly sound. An examination of the corroded portion, kindly made by Prof. E. F. Herroun, F.I.C., shows that it consists mainly of alumina and metallic aluminium. It also contains sulphate in appreciable quantity, and a trace of chloride, also traces of iron probably derived in part from the emery paper, but no zinc or nickel.

(II) Aluminium-Copper.

It will be seen in Table 1 that specimens 16, 4, 13, 14 and 15, contain copper in ascending order of magnitude, and 24 is an aluminium-copper alloy containing a definitely larger proportion of iron. Referring to the curves in Fig. 1, which are numbered to correspond to the specimen numbers in Table 1, it is seen how greatly the slope increases with the percentage of copper. The deterioration of alloy 15 progressed so rapidly that its useful life was reduced to a few years, and it is followed by 14 and then 13. Specimens 4, 16 and 24 have steadily diminished in conductivity to about the same extent.

Referring to Table 4 it will be seen that these three specimens have lost comparatively little metal by corrosion. Their initial resistance, R_0, compares favourably with that of 25, and the final resistance R_t is in the case of specimens 16 and 4 considerably better than that of 25.

It is interesting to note that the unexposed alloy 4 (Table 2) shows practically no alteration in specific resistance.

(III) Aluminium-Nickel-Copper.

Specimens 7, 8, 20, 21 and 22, forming this group are all in good condition; in fact some of them seem

to be almost as good mechanically as when first exposed in 1901. Alloys 21 and 22 are remarkable on account of their high breaking load, and 22 differs from the rest in that its temperature coefficient of electrical resistance is about one-half that of the others.

that there is initially a small increase in conductivity. In alloy 22, conductivity has dropped in seven years to about 84 per cent, and, judging from the behaviour of the copper alloys (Fig. 1), one might have thought that this alloy (22) was so far deteriorated as to be of

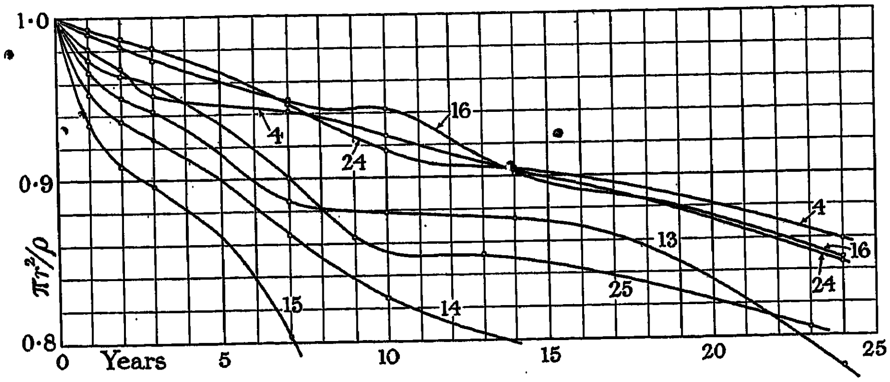

FIG. 1.—Aluminium-copper.

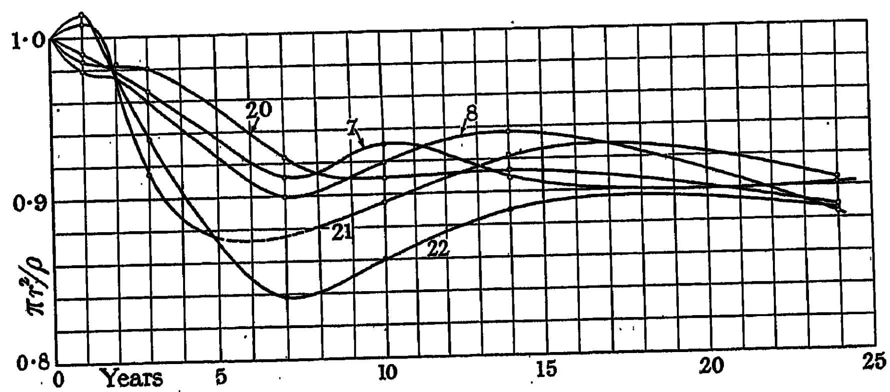

FIG. 2.—Aluminium-nickel-copper.

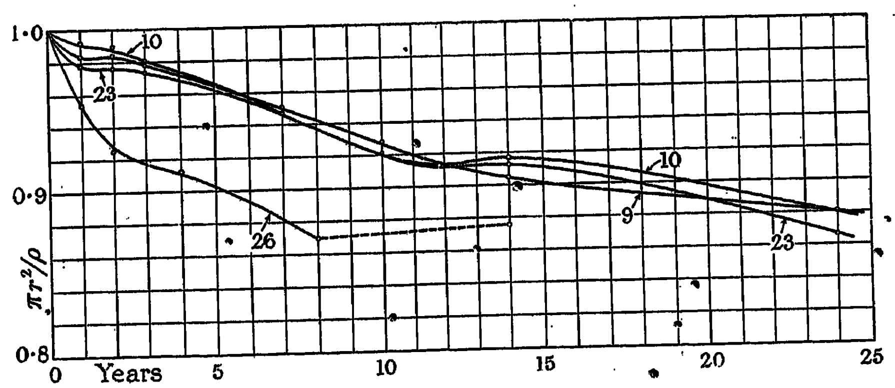

FIG. 3.—Aluminium-manganese-copper.

The type of curve in Fig. 2 differs from that in Fig. 1 in that the initial fall is followed by a remarkable recovery. It would appear that, in addition to corrosion, the structure of the alloy has changed in such a manner as to increase its conductivity. This effect is so strongly marked in the case of alloys 21 and 22,

little use. This is not the case and the specimen after 24 years' exposure is not only in good condition but has a conductivity 88·5 per cent of its original value.

The unexposed specimens 8 and 22 (Table 2) show that specific resistance has diminished to the extent of 2·44 and 3·05 per cent respectively. It may be that

under the exposed conditions the diminution is more severe, and if this were so it might throw light upon the type of curve shown in Fig. 2.

It will be seen in Table 4 that all the specimens with time, and there is no rapid fall followed by a rise, as in Fig. 2. The unexposed specimen 23 (Table 2) shows an increase in conductivity amounting to 2·01 per cent in 24 years. The increase in resistance (Table 4)

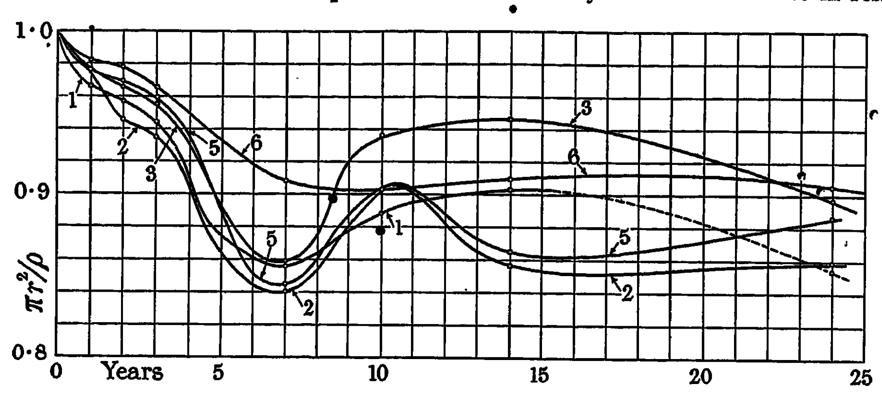

FIG. 4.—Aluminium-zinc-copper.

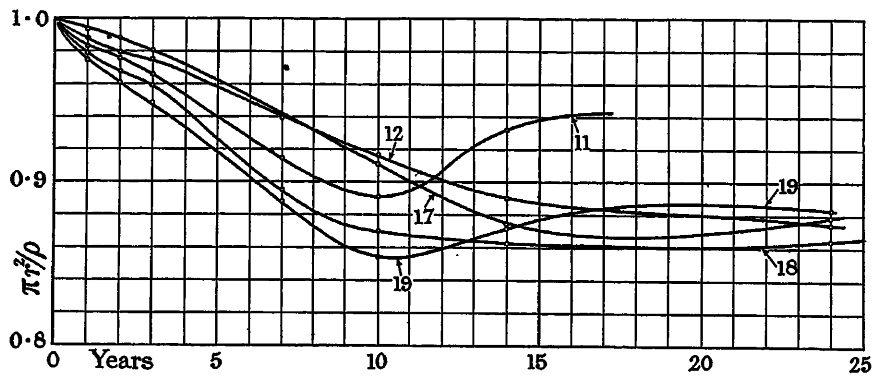

FIG. 5.—Aluminium-zinc-nickel-copper.

forming this group have suffered but little by loss of metal. Nos. 7, 8 and 20 are exceedingly fine alloys as none of them has suffered great variation in conductivity (Fig. 2). No. 7 has an initial resistance, R_0, due to loss of metal is very small in the case of all the conductors forming this group. No. 10 is the best so far as the initial and final resistances (R_0, R_t) are concerned.

TABLE 3.

Values of R_t/R_0 at End of Stated Intervals.

Metal	1911–12	1911–13	1911–15	1915–16	1915–19	1919–25
Copper (annealed)	1·012	1·020	Specimen missing	—	—	—
Copper (annealed)	—	—	—	1·0054	1·0224	0·9954
Copper (hard-drawn)	—	—	—	1·0002	1·0187	0·9958
				1911–16	1911–19	
(26) Duralumin	1·051	1·082	1·096	1·110	1·150	0·9941
(25A) Aluminium	1·037	1·044	1·073	1·102	1·150	0·9977

slightly higher than that of 25, but the final resistance, R_t, is smaller.

(IV) ALUMINIUM-MANGANESE-COPPER.

The alloys 9, 10 and 23 (Fig. 3) like the low-percentage copper alloys (Fig. 1) steadily diminish in conductivity

The actual specimen of duralumin (26) exposed has not been chemically analysed as in the case of all the other alloys, and it is stated to contain from 3·5 to 5·5 per cent copper, 0·5 to 0·8 per cent manganese, and about 0·5 per cent magnesium. After eight years' exposure its conductivity has fallen to 87 per cent

TABLE 4.

Group	Number of specimen	Time of exposure t	Specific resistance in microhms/cm³ at 15° C. ρ_0	Area of section a_0	Resistance per cm in microhms at 15° C. R_0	Specific resistance in microhms/cm³ at 15° C. ρ_t	Per cm grammes lost / sp. gr. b_t	Resistance per cm in microhms at 15° C. R_t	$a_0 - b_t$	ρ_t/ρ_0	$\frac{a_0}{a_0 - b_t}$	R_t/R_0 Calculated	R_t/R_0 Observed
		years		cm²									
I	25A	8	2·773	0·08066	34·39	2·943	0·009100	41·12	0·07156	1·061	1·127	1·193	1·150
	25	23	2·773	0·08066	34·39	3·032	0·011120	43·67	0·06954	1·093	1·160	1·269	1·240
II	16	24	2·83	0·07940	35·64	3·289	0·002722	42·94	0·07668	1·162	1·035	1·203	1·184
	4	24	2·88	0·07917	36·38	3·187	0·003639	42·20	0·07553	1·107	1·048	1·160	1·140
	13	24	3·30	0·07940	41·56	4·113	0·003348	54·09	0·07605	1·246	1·044	1·301	1·280
	24	24	2·955	0·07940	37·22	3·411	0·002490	44·40	0·07690	1·154	1·032	1·191	1·183
III	7	24	3·05	0·07965	38·30	3·327	0·001983	42·83	0·07767	1·091	1·025	1·119	1·110
	8	24	3·24	0·07965	40·76	3·634	0·001318	45·68	0·07833	1·121	1·017	1·140	1·130
	20	24	3·14	0·07933	39·58	3·484	0·001451	44·73	0·07788	1·110	1·019	1·130	1·127
	21	24	3·195	0·07988	40·00	3·454	0·002275	44·51	0·07760	1·081	1·030	1·113	1·106
	22	24	3·28	0·07917	41·44	3·797	0·002330	48·97	0·07654	1·144	1·030	1·183	1·130
IV	10	24	3·09	0·07965	39·80	3·413	0·004115	45·20	0·07554	1·105	1·054	1·165	1·140
	9	24	3·30	0·07925	41·64	3·642	0·002195	47·25	0·07706	1·104	1·019	1·124	1·136
	23	24	3·35	0·07965	42·06	3·683	0·003850	48·60	0·07580	1·100	1·051	1·156	1·160
V	1	24	2·86	0·07933	36·05	3·143	0·004746	42·14	0·07458	1·099	1·063	1·170	1·210
	2	24	2·94	0·07933	37·06	3·222	0·005570	43·68	0·07376	1·096	1·075	1·179	1·165
	5	24	3·07	0·07980	38·47	3·368	0·003056	43·87	0·07674	1·097	1·040	1·141	1·127
	3	24	3·06	0·07910	38·68	3·406	0·002086	44·24	0·07701	1·113	1·027	1·143	1·115
	6	24	3·12	0·07910	39·53	3·442	0·002334	44·61	0·07677	1·103	1·030	1·136	1·120
VI	17	24	3·005	0·07925	37·92	3·389	0·002654	44·26	0·07660	1·128	1·034	1·166	1·140
	12	24	3·18	0·07949	40·00	3·474	0·002593	45·21	0·07690	1·092	1·034	1·130	1·139
	18	24	3·245	0·07965	40·74	3·569	0·002896	46·50	0·07675	1·100	1·038	1·142	1·156
	19	24	3·205	0·07933	40·40	3·555	0·001769	45·84	0·07756	1·109	1·023	1·134	1·130
	11	24	3·48	0·07949	43·80	3·787	0·001514	48·56	0·07798	1·088	1·019	1·109	1·109

of its initial value, and shows no sign of recovery. It is possible that the high copper content is responsible for this. The dotted portion of curve 26 indicates the slight recovery due to rest in the Laboratory (Table 3). It was pointed out (British Association Report, 1913) that this alloy becomes brittle on exposure, and this is evidence that it undergoes severe physical change.

(V) Aluminium-Zinc-Copper.

All the alloys (Fig. 4), with the exception of 6, have shown an initial fall in conductivity followed by a rapid recovery. Alloy 6 with small loss of metal (Table 4) has maintained a very steady conductivity (Fig. 4) but its initial and final resistances (R_0, R_t), are rather high. No. 1 is superior in this respect, but its conductivity suffers considerable variation during exposure, and it has suffered a greater loss of metal.

(VI) Aluminium-Zinc-Nickel-Copper.

The initial fall in conductivity (Fig. 5) is more gradual, and in the case of specimens 12, 17 and 18 a fairly stable condition is ultimately attained. Specimens 11 and 19 exhibit a considerable increase in conductivity after having passed the minimum.

Alloy 11 has maintained a relatively high conductivity, and the increase in resistance due to diminished volume is small. With the exception of 17, the values of R_0 and R_t are somewhat high. The loss of metal throughout is small, and increased specific resistance largely accounts for the increase in resistance.

(VII) Copper.

The results of the copper exposure tests are given in Table 3. The specimens are about 80 ft. long and have a diameter of 0·126 inch (3·2 mm), and were supplied as high-conductivity copper in the annealed and hard-drawn conditions. The percentage increase in electrical resistance during the first year is greater in the annealed than in the hard-drawn state, and after four years' exposure the hard-drawn wire has a somewhat lower percentage increase, the figures being 2·24 and 1·87 respectively. The specimens were then submitted to a rest of six years in the Laboratory, being loosely coiled up, and during this period a small diminution in electrical resistance has been observed.

The author wishes to express his thanks to the British Aluminium Company, Ltd., for their kindness in supplying the note on what is now meant by "commercial aluminium."

THE TWO-SPEED CASCADE INDUCTION MOTOR.*

By A. H. M. ARNOLD, B.Eng., Student.

(*Paper first received 23rd February, and in final form 5th May,* 1925.)

SUMMARY.

The general conditions of operation of two motors in direct and differential cascade are considered, with special reference to the possibility of the set running at a speed near the synchronous speed of the primary machine, while still connected in cascade.

Hunt's cascade motor is next described. The theory of the superposition of two fields in one magnetic circuit is given, and vector diagrams are drawn of the M.M.F. to be produced by the rotor windings at each point. The superposition of two currents of different frequency in the stator windings is next dealt with, and an account is given of the experimental work carried out to verify this theory, by means of oscillograph records of the currents flowing in the various coils of the stator windings of the motor tested.

TABLE OF CONTENTS.

The research carried out is based on the paper by L. J. Hunt, entitled "The Cascade Induction Motor" (see *Journal I.E.E.*, 1914, vol. 52, p. 406).

(I) SPEED OF CASCADE MOTORS, OR SPEED OF TWO MOTORS CONNECTED IN CASCADE.

The theory of cascade running is well known, and the formula by which the synchronous speed of a cascade set may be determined is given below.

Let R be the speed in revolutions per second (r.p.s.) of the two machines at synchronous speed. The motor connected to the supply mains will be referred to as the primary motor, whilst the other will be referred to as the secondary motor.

Let P_1 and P_2 = the numbers of pairs of poles for which the motors are wound.

N = the frequency of the supply circuit.

Then the synchronous speed of the set is

$$R = \frac{N}{P_1 + P_2}\ \text{r.p.s.} \quad \text{or} \quad \frac{60\,N}{P_1 + P_2}\ \text{r.p.m.}$$

If two of the leads from the primary rotor to the secondary stator are interchanged, so that the secondary field rotates in the opposite direction, then $R = N/(P_1 - P_2)$ r.p.s. This is known as "differential cascade." *

It should be noted that in this latter case the torques of the two motors are opposed to each other, so that the resultant torque is equal to the difference of the two torques. The performance of the set is, therefore, generally very poor.

If P_1 is less than P_2, rotation takes place in the direction of the magnetic field of the secondary machine. The frequency of the currents in the rotor of the primary machine and the stator of the secondary machine is then higher than the supply frequency, with resultant high iron losses.

If P_1 is greater than P_2, rotation takes place in the direction of the magnetic field of the primary machine, and a stable speed is reached just below the synchronous speed of the primary machine. Above the synchronous speed of the primary machine there is a zone where the torque of both machines becomes negative, and regeneration of power takes place. Beyond this zone the primary machine begins to motor again, and its torque finally predominates over the negative torque of the secondary machine and a stable speed is reached below the synchronous speed of the set. It is therefore evident that, with this method of connection, the motors must be brought up to speed by external power. This may sometimes be done by running the machine with the smaller number of poles as a plain induction motor and then, when the set has passed the generating zone, changing over the connections to differential cascade. The advantage of this method of connection is that the frequency of the currents circulating between the two machines is lower than with the first method. Differential cascade sets have a very limited application.

When two motors are connected in direct cascade, it is also possible for them to run at the synchronous speed of the primary machine, but in this case the speed is higher than cascade synchronous speed, and when the set is started up from rest it reaches a stable speed just below cascade synchronous speed and therefore does not increase its speed further. The point is of importance, however, if, as in most cases, the set has change-over switches, so that the primary machine can run as a plain induction motor at a speed near the primary synchronous speed, while the secondary machine is disconnected electrically. (If $P_1 = P_2$, then both machines may be connected in parallel to the mains.) If, while running at this higher speed, the switch is changed over to cascade connection, provided that the resisting torque is below a certain value the

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

* See C. DELLA SALDA: "Induction Motors in Differential Cascade," *Elettrotecnica*, 1922, vol. 9, p. 266.

set will continue to run at the higher speed, instead of dropping to the cascade speed. This applies equally, of course, to Hunt's two-speed cascade motor, the higher speed being the speed of the machine as a simple induction motor. On light loads, changing over the connections will not bring the speed of the machine down to cascade speed.

The theory of this will now be considered, and an actual example will be taken to illustrate it. Consider a 50-cycle, 4-pole–4-pole cascade set running at about 1 450 r.p.m. with both machines in parallel on the mains. The connections are now changed over, so that one machine is supplied from the rotor of the other. The frequency of the currents now flowing in the stator of the secondary machine will be about 1 cycle, or the speed of magnetic field will be 50 r.p.m., while the rotor is rotating at 1 450 r.p.m. The slip is therefore

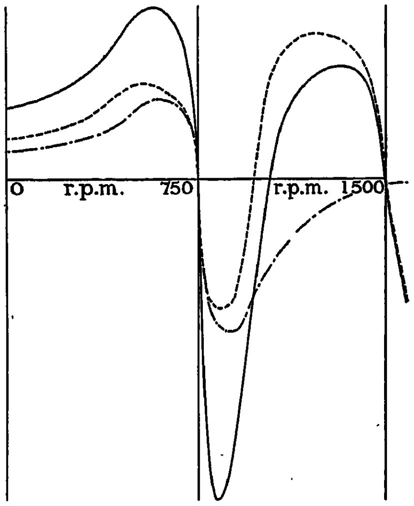

FIG. 1.—Shaft torque of two motors connected in direct cascade. Synchronous speed of cascade set = 750 r.p.m.; synchronous speed of primary motor = 1 500 r.p.m.

negative, so that the torque becomes negative and regeneration takes place. This causes an increase of slip for the primary machine, i.e. a reduction in speed of the set, and the torque of the primary machine rises until it is sufficient to offset the negative torque of the secondary machine. It should be noted that, as regeneration takes place, no extra power is required from the mains beyond that necessary to supply the extra copper losses involved, so that the secondary machine really acts simply as an impedance and increases the losses of the set. It receives its power through the shaft from the primary machine and regenerates electrical power back to the rotor windings of the primary machine. As, however, the primary machine has now to offset the negative torque of the secondary as well as to overcome the external torque, the slip will increase in order to provide the additional torque. The maximum external torque which the machine is capable of overcoming will be reduced, and if the external torque exceeds this, the speed will drop to cascade speed, when both motors will once more exert a positive torque and a stable speed will be obtained (see Fig. 1). Methods have therefore to be devised of lowering the speed of a cascade set from its high speed to its cascade speed, if the load is not sufficient to accomplish it automatically when the connections are changed over. With moderate loads the speed may be lowered by inserting resistances into the rotor circuits until the increased slip makes the speed equal to cascade speed, when the change-over may be effected. If the load is very small, or if there is no load at all, the amount of external resistance required may be excessive. In this case the only way of lowering the speed is to switch off the main supply, change over the connections, and then, when the speed has fallen to cascade speed, switch in again.

Fig. 1 also shows that with cascade connections there

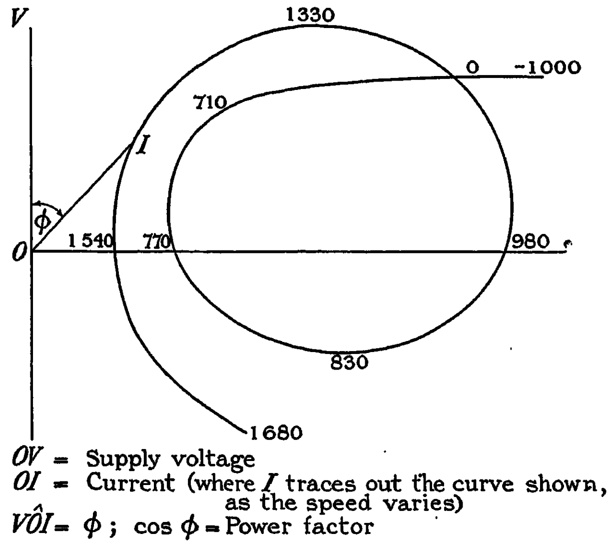

FIG. 2.—Circle diagram of two motors connected in direct cascade. Synchronous speed of cascade set = 750 r.p.m.; synchronous speed of primary motor = 1 500 r.p.m. The figures indicate the approximate speed in r.p.m. at various points of the curve.

are two zones of regeneration, and Fig. 2 shows the power factor of regeneration and the current. In the upper speed zone (above 1 500 r.p.m.) regeneration at a better power factor and with a smaller slip may be obtained by disconnecting the secondary machine and using the primary machine as a plain induction generator.

In the lower-speed zone (above 750 r.p.m.) the power factor of regeneration is very poor, and there is the additional disadvantage of the danger of the machine passing the peak of the regeneration curve, when it would immediately run up to double its speed unless the driving unit were capable of checking it.

All the above remarks apply equally well to a cascade set of two machines, or to Hunt's cascade motor. Hunt's motor will now be considered in more detail.

(2) THEORY OF HUNT'S CASCADE MOTOR.

The disadvantages of the ordinary cascade set are low power factor and low output for a given amount

of machinery. The reasons for this are well known, but are recapitulated here very briefly. The mains have to supply the magnetizing current for both machines, whilst the output of the two machines in cascade is less than the output of one machine at normal speed. This results in a small load current and large magnetizing current, thus giving a poor power factor.

The reason for the reduced output is that the circle diagram of the two motors in cascade is very much reduced in size, since the magnetizing current is increased to double, as stated above, whilst the short-circuit current of the set is considerably less than for one machine alone. This gives a small diameter to the circle and consequently reduced output.

In Hunt's motor the power factor at cascade speed is poor, as is that of two motors in cascade, and the circle diagram is very similar in size. The chief advantage lies in combining the two machines in one frame and thus reducing the cost of construction and the space occupied. The copper losses are considerably reduced owing to the cancelling out of the equal currents which tend to flow in opposite directions in the superposed windings, and the efficiency is therefore found to be higher than that of an equivalent cascade set of two machines.

Although the power factor of a cascade set or of Hunt's motor at cascade speed is poor compared with that at the higher speed, it is not necessarily bad when compared with the power factor of an ordinary induction motor running at the lower speed, since the magnetizing current increases with the number of poles. The motor under test was a comparatively high-speed machine (500 r.p.m. cascade speed) and therefore does not compare so favourably with a plain induction motor at the same speed as a lower-speed machine would do. With abnormally low speeds the power factor is sometimes better than that of an ordinary induction motor running at the same speed.

It should first be noted that a cascade set will run equally well if the rotor windings of the primary are connected to the rotor windings of the secondary and the stator of the secondary short-circuited. In this case the connections must be so made that the magnetic field in the secondary rotates in the opposite direction to the field in the primary, as it will be necessary at synchronous cascade speed for the field to be stationary relative to the stator windings of the secondary. This is obtained when the rotor rotates in one direction at a speed equal to the speed of the field in the other direction.

With this method of connection slip-rings are abolished and starting resistances may be inserted in the stator of the secondary, the two rotor windings being permanently connected. This, of course, applies only if cascade speed alone is required; if, in addition, the normal induction-motor speed is required, slip-rings will be necessary to obtain it.

The next stage in Hunt's motor is to combine the two machines in one. This can be considered in two parts, the rotor and the stator.

(*a*) *The rotor.*—The rotor will not be dealt with at length here, as no investigation upon it was carried out. In the machine tested, the rotor has a winding in which it is impossible to get tappings without damaging the windings and insulation, so that the only data obtainable were of the current flowing to the slip-rings with the machine running at the higher speed. This was found to be a fairly sinusoidal wave with a few ripples, as will be seen from Fig. 3.

The rotor is dealt with at length in Mr. Hunt's paper, and also in a new and more effective way in Mr. Creedy's.

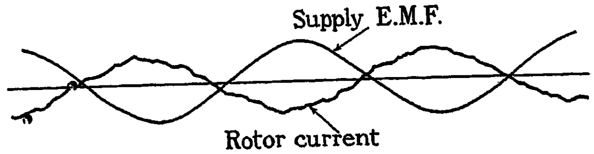

FIG. 3.—Motor at non-cascade speed and no load.

This record was taken with two of the slip-rings short-circuited through the oscillograph to the third ring.

paper.* A short résumé of Mr. Creedy's line of reasoning will be given here, in order to maintain the continuity of the report, but it should be clearly understood that no experimental verification was obtained, beyond the fact that the motor operated satisfactorily at both the cascade speed and the higher speed. An attempt was made to get an idea of the distribution of the flux in the air-gap. This will, however, be dealt with later.

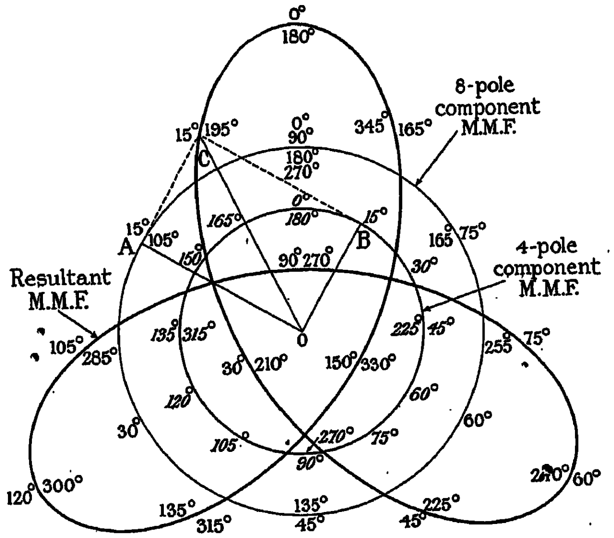

FIG. 4.—Vector diagram of M.M.F. of 8-pole–4-pole rotor. Positions round rotor in degrees are marked on curves, e.g. at 15° from starting point OA = vector representing in phase and magnitude 8-pole component M.M.F.; OB = vector representing in phase and magnitude 4-pole component M.M.F.; and OC = vector representing in phase and magnitude resultant M.M.F.

To simplify the explanation, an actual case will be taken, and the one considered will be that of the motor on which the experiments were carried out. This machine was an 8-pole–4-pole machine, running at 8-pole speed (750 r.p.m.) for one speed, and at cascade or 12-pole speed (500 r.p.m.) for the other speed. During cascade running, the currents in the stator windings produce an 8-pole field rotating at 750 r.p.m.

* *Journal I.E.E.*, 1921, vol. 59, p. 511.

The rotor winding if wound for 8 poles will have currents induced in it, and if this is connected in series with another rotor winding wound for 4 poles it will produce a 4-pole field rotating in the opposite direction. Actually neither field exists separately, but only a compound field. If the nature of this field is discovered, then a single rotor winding may be developed to produce it, and the cascade effect will be obtained with only one winding.

Space/time vector diagrams must now be introduced. If for each point on the rotor a vector be drawn representing the value and time-phase of the flux at that point, then a curve may be drawn joining the ends of these vectors to show the maximum (or R.M.S.) value of the flux at any point on the rotor and also its time-phase with respect to other points. As an example, take a 4-pole field distributed in space according to a sine wave. As we proceed round the rotor, the vector

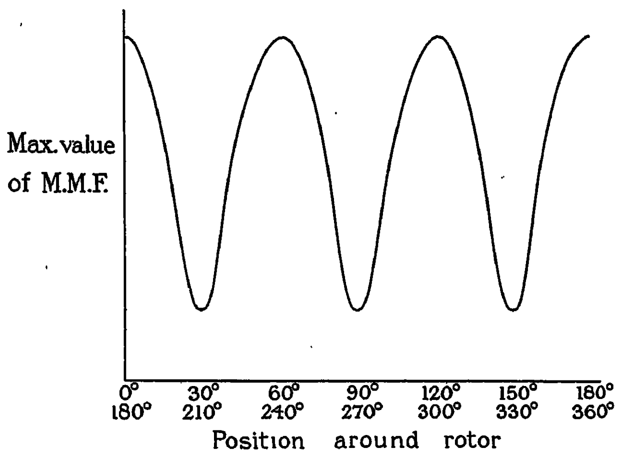

FIG. 5.—Diagram showing how the maximum value of the M.M.F. varies round the rotor for an 8-pole–4-pole field. It does not show the phase relationships of these M.M.F.'s, which must be obtained from Fig. 4 as explained there.

representing the flux maintains the same value but completes a circuit of the diagram twice while we go round the rotor once. The flux distribution is therefore represented on this diagram by a circle, and each point on the circle will correspond to two distinct points on the rotor, since there will be two points on the rotor, 180° apart, which have the same value of the flux at the same instant. Similarly, with an 8-pole field a circle will be obtained, each point of which corresponds to four positions on the rotor. It can be seen, therefore, that the flux in a sinusoidal field may be represented by a vector, which rotates p times in one circuit of the rotor, where p = number of pairs of poles. These vectors can be compounded similarly to other vectors, and in our case let us compound an 8-pole field and a 4-pole field rotating in opposite directions.

Starting from a point where the two fields have their maximum value together, we mark this by a vector equal to the sum of the two fields, drawn vertically upwards. Proceeding, say, 15° round the rotor, the 4-pole vector will have rotated through 30° in one direction, and the 8-pole vector 60° in the other direction. Compounding these two, we get the actual value of the flux at that point in time and magnitude. Proceeding thus in steps of 15°, a series of points may be plotted which may be joined up in a smooth curve. This curve will be found to repeat itself in the second half of the rotor. A reproduction of the curve is given in Fig. 4. The shape will depend to a certain extent on the relative values of the 8-pole and 4-pole fields, but the general form will remain unaltered, and the

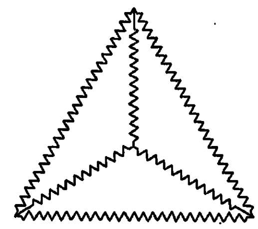

FIG. 6.

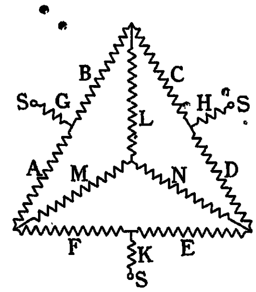

FIG. 7.

chief feature of the rotor at once stands out. This is, that the ampere-conductors at different parts of the rotor will be different. A winding may now be devised to conform as closely as possible with the curve below, and Mr. Creedy gives examples of these. They are thought out without any reference to the two component fields, and in conformity with the diagram, so as to obtain the required resultant field.

Mr. Hunt's treatment is somewhat different, and consists of taking the two windings, superposing them,

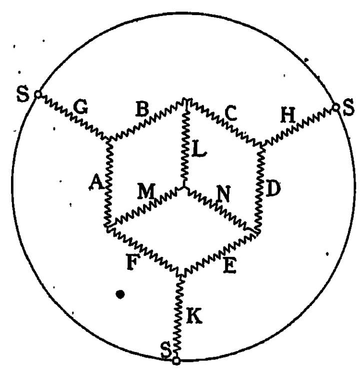

FIG. 8.

and then cancelling the bars which carry currents of equal value in opposite directions. This method is complicated and is not so universally applicable as Mr. Creedy's.

Having constructed a winding in accordance with the above M.M.F. diagram, the rotor will operate satisfactorily at cascade speed. When, however, the machine is required to run at the higher speed it is necessary to distribute the M.M.F. sinusoidally around the rotor so as to give an 8-pole field. As the slots in a motor are all of the same size, those slots which only carry a few bars (that is, where the M.M.F. required for cascade speed is low) are filled with idle bars. When the higher

speed is required, these bars are connected into the rotor winding by short-circuiting the slip-rings (through resistances at first) and thus effecting an even distribu-

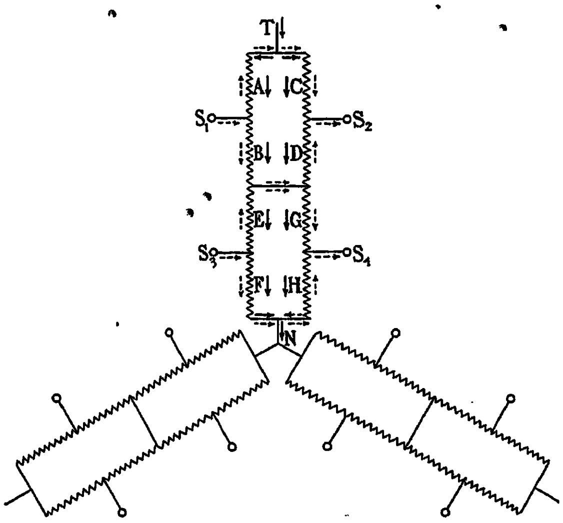

FIG. 9.—Key diagram of stator winding.
Primary currents ⟶ Secondary currents - - →

tion of M.M.F. The method of connecting these idle bars is clearly shown in Mr. Hunt's paper.

The normal cascade winding for Mr. Hunt's motor is one end and to the middle parts of the delta winding at the other end. The resultant winding is shown in Fig. 7. When the slip-rings are short-circuited the phases of the currents in the various branches are altered, and the resultant winding becomes four inter-connected star windings (see Fig. 8). A circle shows the points short-circuited by the slip-rings. Corresponding coils in Figs. 7 and 8 are lettered. The reasoning by which Mr. Hunt shows this winding to give the required M.M.F. is best followed in his paper.

(*b*) *The stator.*—The treatment of the stator winding is quite different and will be considered in detail, and an account will be given of the experimental verification of the theory of this winding by means of oscillograph records of the currents in the various branches of it.

The stator winding in the machine under test was star-connected and was wound for 8 poles. Each phase consisted of two circuits in parallel. Three-phase currents were supplied to this stator from the external supply at supply frequency, i.e. 50 cycles, and circulated in the windings in the usual way. These currents produced an 8-pole field, and the currents induced by this 8-pole field in the rotor reflected back a 4-pole field in the manner described in the previous section.

The stator has now to be so designed that the E.M.F.'s induced by this 4-pole field may be able to circulate currents in the windings without affecting the high-

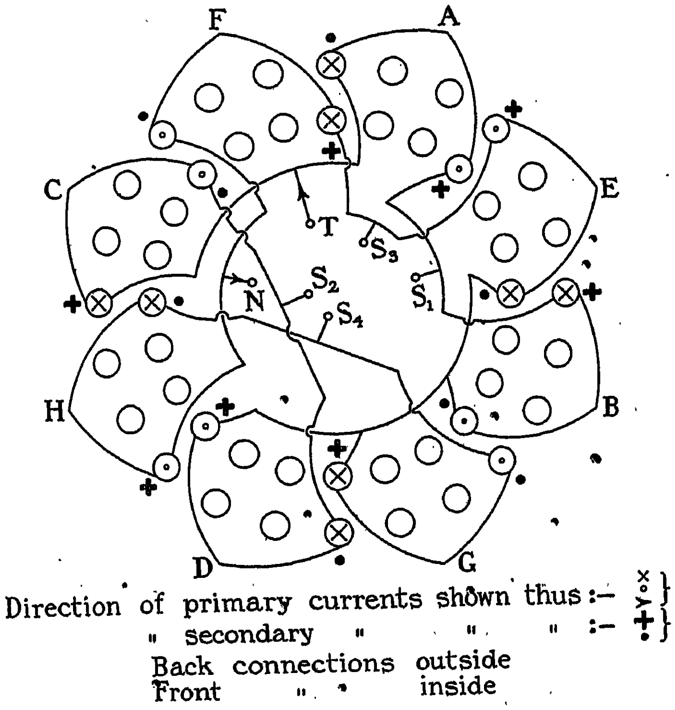

FIG. 10.—Stator winding diagram.

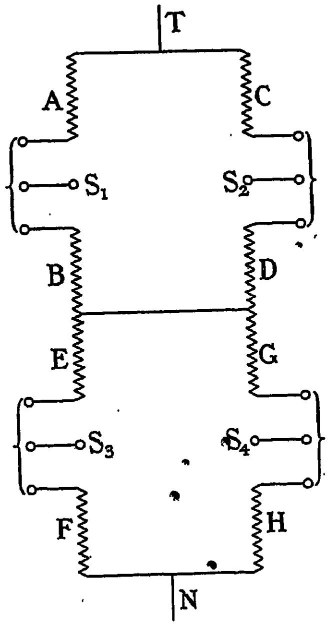

FIG. 11.—Experimental tapping points, stator phase.

a star-mesh winding, as shown in Fig. 6. This winding will produce the required magnetomotive force as Mr. Hunt shows, although others will do so also.

Mr. Hunt connects the idle bars to the slip-rings at frequency supply currents. Tappings must also be obtained for the insertion of resistances during starting, and these tappings must be taken from points at which there is no P.D. due to the supply current. This at

once gives the reason for the stator winding having parallel circuits, and the key diagram for the actual stator winding is given in Fig. 9.

Since the stator is wound for 8 poles, the coils will be only half-pitched with respect to the 4-pole field. Consequently, adjacent coils of the same phase will have their maximum E.M.F. 90° displaced from each other in time, so that in order to use the windings to the best advantage, two-phase currents will have to be arranged for. In the winding, coils A, B, C and D alternate with coils E, F, G and H (see winding diagram, Fig. 10), so that the secondary currents in A, B, C and D are in phase with each other and 90° out of phase with the currents in E, F, G and H. The windings are strapped across at the mid-point, as shown in Fig. 9, and are so arranged that the secondary currents flow from the tapping points [s_1 s_3] on each side through the windings and straps to the tapping points [s_2 s_4] on the other side. For starting, these tapping points are connected through resistances, and during normal running they are short-circuited in pairs [s_1 s_2 ; s_3 s_4]. Since the points at which tappings are taken are equipotential with respect to the supply current, they will not cause any disturbance to this current.

The main current is shown by full arrows in the key diagram (Fig. 9) and winding diagram (Fig. 10), and the secondary currents by dotted arrows. It will be seen that the two diagrams agree. The directions of currents in the winding diagram are obtained from the usual rule for magnetic fields. For operation at non-cascade speed it is immaterial whether the starter tapping points are short-circuited or open-circuited. At non-cascade speed the stator only carries the high-frequency supply current, the machine operating as an ordinary induction motor. The tapping points are, therefore, equipotential points, and no change is made in the electrical conditions by short-circuiting them.

TABLE.

Particulars of Motor on which the Investigations were Made.

Hunt's two-speed cascade motor, manufactured by Messrs. Sandycroft, Ltd., Chester.

200 volts	50 cycles	3-phase
10 b.h.p.	710 r.p.m.	30·5 amps.
6$\frac{3}{4}$ b.h.p.	480 r.p.m.	21·5 amps.

No. of stator slots = 72.

OSCILLOGRAPH INVESTIGATION.

An oscillograph investigation of the currents flowing in the various coils of the stator winding was made in order to confirm the theory outlined in the paper. Tappings were taken from the stator winding and brought out to a terminal board in accordance with Fig. 11. Each group of these terminals was normally short-circuited, but by disconnecting the short-circuiting strap the current in any coil could be sent through the oscillograph before returning to the machine.

On no load at cascade speed these currents were found to be nearly pure sine waves. As the high-frequency magnetizing current is very large at no load compared with the low-frequency secondary current, the resultant stator current is practically identical with the magnetizing current.

On full load the low-frequency current is comparable in magnitude with the high-frequency current, and the resultant current differs considerably from a sine wave. As the frequencies were very different, during one complete period of the high-frequency current the low-frequency current did not alter much, so that the resultant wave approximated to a sine wave with a constantly shifting centre line. A curve drawn through successive maximum points of the resultant wave thus

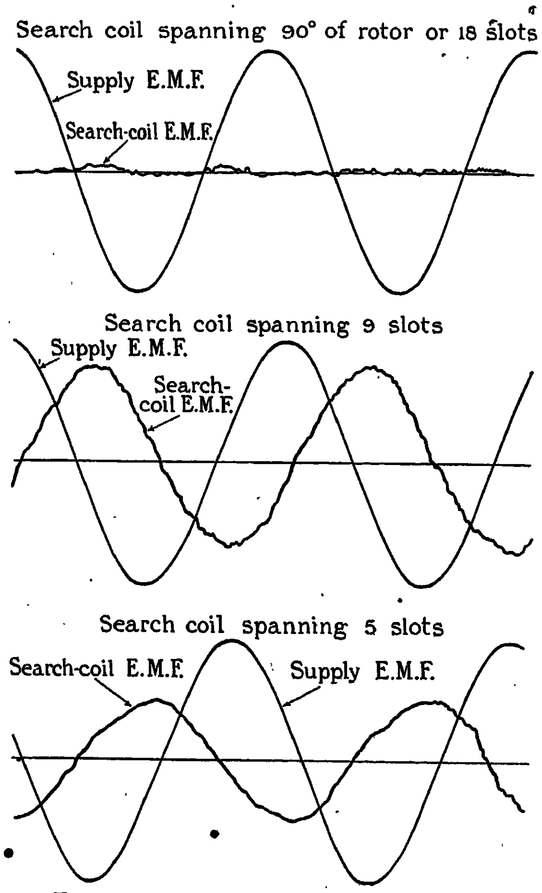

FIG. 12.—Motor on load at cascade speed.

gave a very fair approximation to the low-frequency current. Owing to unevenness in the belt drive to the load, the high-frequency current was not constant and thus the curve drawn through the maximum points was not a true representation of the low-frequency current. It was sufficiently accurate to enable the maximum and minimum points to be approximately determined, but it was useless to analyse the harmonics, as these varied from point to point.

Reproductions of the secondary currents analysed from the film records, and also a portion of the film, are shown in the oscillographs Figs. 13 and 14. It was found that the secondary currents in coils A, B, C and D were in phase with one another and in quadrature with

the currents in coils E, F, G and H. The primary currents were in phase with each other in all the coils. This confirms Mr. Hunt's theory.

Search coils were wound on the stator spanning 18,

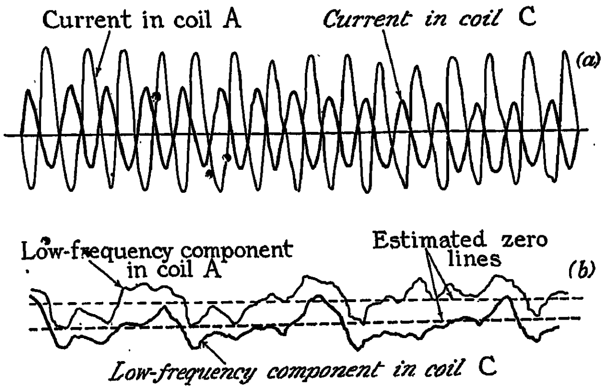

FIG. 13.—Oscillograph records of currents flowing in stator coils with the motor on load at cascade speed.

(a) Portion of film record obtained. NOTE: The scale for the currents in the two coils was made different in order to be able to distinguish them. The currents were actually of the same magnitude.
(b) Low-frequency components of current in stator coils analysed from film record, a portion of which is shown in (a) above. These are in phase with each other.

9 and 5 slots, i.e. a pole-pitch for the 4-pole field, half a pole-pitch, and a quarter pole-pitch. Oscillograph records with the motor operating on load at cascade speed are shown in Fig. 12. The 8-pole flux produced

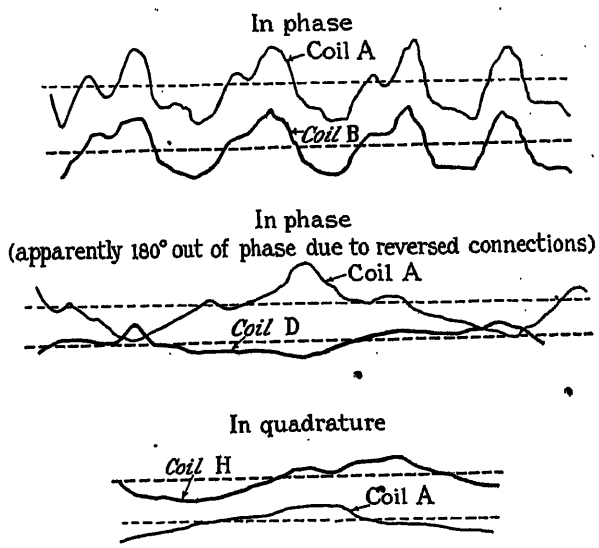

FIG. 14.—Low-frequency component currents in stator coils.

NOTE: (1) The current scales are different in each case for the two currents compared, in order to distinguish the curves.
(2) The time scale is not the same in different cases, due to the film being passed through at different speeds.
(3) The currents were not analysed for coils E, F and G, as the theory was sufficiently well established by the analysis of the currents in coils A, B, C, D and H.

by the stator is rotating relatively to the search coils at a high speed, while the 4-pole flux produced by the rotor cuts the search coils at a low speed. The E.M.F. induced is, therefore, almost entirely due to the 8-pole flux, and this is borne out by the oscillograms which show a sine wave in two cases and only a few ripples in the 18-slot span coil.

Owing to the rotor winding being in semi-enclosed slots, it was not possible to wind search coils on the rotor. Such coils would have shown the compound resultant field, as the two fluxes rotate at the same speed relative to the rotor.

The circle diagram of this machine was obtained both for cascade speed and non-cascade speed. It was found that the no-load losses were practically identical at both speeds. At cascade speed the machine took a much larger magnetizing current than at non-cascade speed, but the power factor was lower and the power consumed the same.

It is probable that the iron losses were slightly higher at cascade speed, but this must have been offset by the reduction in windage at the lower speed.

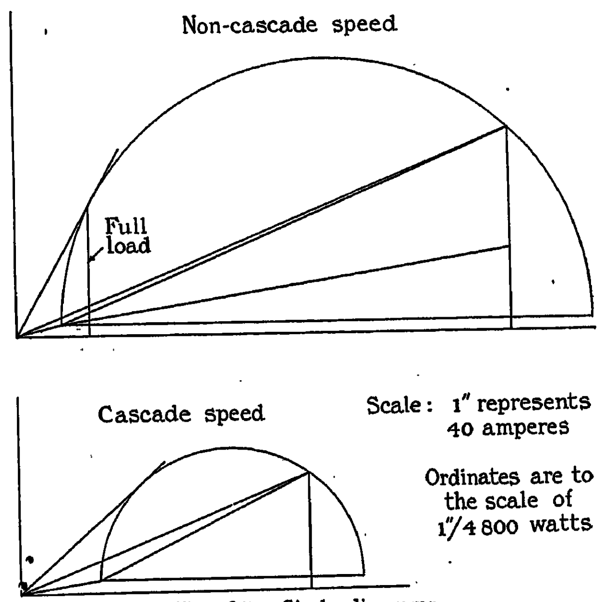

FIG. 15.—Circle diagrams.

A few of the results obtained from the circle diagram and also from load runs are given below. The circle diagram is also reproduced in Fig. 15.

Non-cascade speed (synchronous speed 750 r.p.m.).

No-load current, 9·4 amperes; power factor, 0·23.
No-load losses, 760 watts.
Maximum power factor, 0·88.
Full-load efficiency, 82 per cent.

Cascade speed (synchronous speed 500 r.p.m.).

No-load current, 16·2 amperes; power factor, 0·14.
No-load losses, 830 watts.
Maximum power factor, 0·68.
Full-load efficiency, 73 per cent (approx.).

The experiments were carried out in the Laboratories of Applied Electricity, The University, Liverpool, and the author's thanks are due to the Faculty of Engineering and Professor E. W. Marchant, D.Sc., for per-

mission to publish the results obtained. Thanks are also due to Prof. Marchant and Mr. J. C. Prescott for the assistance and guidance given in the experimental work and in the preparation of the paper.

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DISCUSSION ON "ELECTRIC PASSENGER LIFTS." *

WESTERN CENTRE, AT PLYMOUTH, 2 FEBRUARY, 1925.

Mr. T. Hood: The paper appears to deal almost exclusively with lifts operating with direct-current equipments, and I should feel obliged if the author would say what his experience has been in respect to alternating-current equipments for passenger and goods lifts. There are several towns in the West of England, such as Bristol, Cheltenham, Bath and Bournemouth, where public supply is only available from high-frequency single-phase circuits. Can the author say what special characteristics should be observed in single-phase and polyphase motors for lift duty?

Mr. T. Stretton: The author's remarks in regard to the frequent failure of the architect to co-operate with the engineer are timely and to the point. Installations which could undoubtedly be made first-class jobs are being continually spoilt through such lack of early co-operation, and unfortunately it is always the engineer who is blamed for a bad job. No reference is made in the paper to the use of continuous lifts, and I should like to have an expression of opinion from the author as to whether this type of lift would not have been cheaper to install and maintain in many cases where ordinary lifts have been installed. I refer, of course, to installations in buildings of moderate height, say four or five storeys. It may be of interest if I give a description of a novel electric lift installation in Cardiff. A jeweller's strong room is in the basement immediately below his window, and is in the form of a square well. The lid is of the ordinary strong-room door pattern, and is arranged to travel from the top of the strong room to a sufficient height to be out of sight of anyone looking in at the shop window. The jeweller's most valuable stock is arranged on properly designed window shelves which are suspended from the under side of the strong-room lid. At night the whole of this stock is simply lowered into the strong room and the lid locked. In the morning the operation is reversed. There is a great saving of labour and almost perfect security. I agree with the author's contention that long periods of acceleration and deceleration are more pleasant for passengers, but this fact should not be allowed to interfere with the efficiency of any installation. Passengers very soon get accustomed to quick acceleration. This is conclusively proved in the case of colliery winders. I should like to ask the author why more use is not made of flat ropes. The drive is in most cases central and not skew, and I should have thought that the flat rope would have many advantages over the circular rope, including less wear. The author states that with an automatic lift a single passenger obtains complete control over the lift until he has completed his journey, although there may be many passengers waiting at intermediate floors. Surely this

* Paper by Mr. H. Marryat (see vol. 62, p. 325).

is not correct. I am under the impression that each set of buttons on each floor includes a "stop" button so that any waiting passenger can stop the lift.

Mr. W. J. Bache: I have found the energy consumption of lifts to be extremely small, and the bill for energy used is sometimes only a few pence per week. Many of the minor faults that occur could be prevented by frequent and competent inspection, and I consider that lift-users generally do not appreciate the importance of inspecting the mechanism frequently as a means of preventing trouble. Contacts are often too flimsy and should be generously rated. I prefer clapper contacts with carbon blocks to sliding brass or copper contacts. Can the author explain why ropes wear unduly between the sheave and the attachment to the lift gear? Automatic self-closing doors of the Bostwick pattern are needed and I should like to inquire whether there is a satisfactory pattern on the market at a reasonable cost. The need for providing all bearings with renewable bushes should be emphasized. I should be glad if the author would indicate the best method of testing the safety gear of a lift without running undue risk.

Mr. A. C. MacWhirter: Architects are much to blame for not making proper provision for lifts when planning new buildings. They do not provide sufficient space or arrangements for satisfactory lift installation, consequently lift manufacturers are considerably handicapped in their designs. They would be well advised to consult lift experts, who would no doubt be able to show them considerable savings in their constructional and general arrangements. In the past we have looked upon American lift practice as "the last word," entirely on account of their unique requirements in their multi-floor buildings, the lift being (broadly speaking) the only communication from the street to the floors. As a result they have had to develop very high-speed lifts. British manufacturers are, however, now up-to-date with their practice and quite able to improve on their designs to serve our requirements more suitably. Push-button lift control is now giving satisfaction, but, in common with most automatic devices, it requires regular attention if it is to give reliable service. The combination of push button and car switch seems to me the most serviceable and economical kind of controller, as it allows the lift to be controlled by an operator during "rush hours" and by push button during the quieter hours. I should like to know why ball or roller bearings are not more generally used, especially on motors and worm gear shaft, in preference to solid bearings. The starting torque would be much less and consequently the acceleration would be increased. Regarding drum and vee sheave driving, I should like to know what is the difference in the life of the ropes in the two cases. I should imagine that there is bound to be considerable slip on the vee sheave, with resulting increase in wear, as compared with the drum type of driving. Can the author say what is the latest practice in motor windings, i.e. whether series windings are used for assisting starting, and if more than one shunt winding is used for speed regulation? Castor oil seems to be generally used for worm gear lubrication. I have known of cases where this oil has become so gummy that difficulty was experienced in starting the lift after standing overnight—especially in cold weather. I should have thought that a good mineral oil would have been the best form of lubricant for this purpose. The counterweighting of lifts is a very important item, and I believe that the correct practice is to load the counterweight to balance the cage plus 50 per cent of full load. I should like to have the author's views on this important point. On the sheave type of drive I have noticed that certain manufacturers have only two bearings with the load carried externally to the bearings. This practice is, I think, very bad; there should always be an out-board bearing which should be lubricated by means of ring lubricators and not grease cups.

Mr. E. E. Benham: Continuous lifts on the escalator principle have been referred to by one speaker. Lifts of this character for material but not for passengers have been installed in one or two of H.M. ships recently, but it is not possible to give any detailed particulars.

Mr. W. G. Heath: Can the author give any information regarding the self-levelling of lifts at different floors, thus obviating the necessity of footlights and the cage stopping anywhere but at the intended floor?

Mr. C. T. Allan: We have had our Cardiff office 5-passenger lift converted from operator control to automatic, with a resulting much increased service to users of the three floors. Much interesting information has been obtained, such as :—

Distance travelled per day—2·8 miles.
Distance travelled per month—90 miles.
Average trips per day—500.
Passengers—467 per day, 11 300 per month.
Consumption, units—2·3 per mile and 2·73 per passenger-mile.

Percentage of total passengers per floor.

Ground to 1st floor— 6·1 per cent.
Ground to 2nd floor—58·8 per cent.
Ground to 3rd floor—35·1 per cent.

Other figures show that the lift is used almost twice as much going up as coming down. Troubles have been rare, the lift being maintained and inspected monthly by the makers. The lift is illuminated, the light being switched on by means of a spring contact in the floor, operated by the passenger when stepping in.

Mr. H. Marryat (*in reply*): A motor for lift duty must give at least 2½ times full-load torque when starting. For single-phase circuits, therefore, a special type of motor must be employed. There are several suitable machines upon the market, but perhaps the best known are the Bandy motor and the Parkinson motor. These are machines of the commutator type having a shunt characteristic. In both cases the stators are double wound in order to provide means for reversal. In the Bandy motor the shunt characteristic is obtained by means of a shifting brush rocker operating automatically. In the case of the Parkinson motor the brush position is fixed and the effect is obtained by means of a compensating winding and transformer. Polyphase circuits present less difficulty. Slip-ring induction motors give the necessary starting torque. Special windings

providing for two or three speeds must be employed in the case of high-speed lifts. Perhaps the most serious trouble encountered with alternating-current lifts is hum, which becomes intolerable in dwelling houses if special provision is not made to reduce this nuisance to a minimum.

Continuously-running lifts were at one time commonly used both for passengers and for goods. For passenger service they have been abandoned, because if they are run at a speed low enough to be safe they are a great deal too slow for modern ideas of transport, in fact it is quicker to use the stairs. On the other hand, for goods service the idea has been highly developed and is the basis of modern conveyer design.

The description of the jeweller's window lift is extremely interesting. It has been suggested that in areas where window space is of great value the window dressing should be changed in much the same way as described by Mr. Stretton, the new dressing being arranged in the basement and lifted into position, whilst the old dressing—rolled aside for the moment—is then lowered to the basement to be dismantled.

The reasons why flat ropes are not used for passenger-lift work are that the round rope gives a maximum of strength for weight, will lay upon the drum more accurately, will tend to increase its grip upon a traction sheave with increase of load, and will give a longer warning of failure. Apart from these technical reasons it is probable that the cost of a flat rope would be somewhat more than the cost of a circular one.

Mr. Stretton is mistaken in thinking that a stop button is fixed at each floor. That may be done in the case of service lifts, but would never do for a passenger lift because, in a busy office building, no one would get anywhere on account of the continual interruption and reversal of the journey. A stop button is always placed in the car to enable passengers to correct any mistake made in pressing the wrong floor button.

In reply to Mr. Bache, I have not found lift ropes to wear anywhere but where they pass over a sheave. If trouble is found near the anchorage of the ropes to the car or balance-weight, the cause is probably the same as that which produces similar results upon many crane ropes, and is probably associated with too rapid braking or acceleration.

There are several automatic self-closing gates upon the market, but I do not know of one which is entirely satisfactory and at the same time reasonably inexpensive.

The usual way of testing the safety gear is to take a loop in the rope by means of a hemp lashing, which is then cut with a knife. Where the safety gear is controlled by a slack cord it may be brought into action by merely pulling the cord. Governor safety-gear may be readily tested by inserting an adjustable resistance in series with the shunt field of the motor and, when the lift is running, switching in the resistance until the speed increases to the pre-arranged value at which the safety gear is to operate. I entirely agree with all the other remarks made by Mr. Bache.

In reply to the question as to why ball or roller bearings are not more used in lift construction, I would point out that we are dealing with a machine which—because it acts upon a see-saw principle—consumes an absurdly small amount of energy. Energy consumption is a very small part of the running cost, and it is doubtful whether the cost of the massive ball bearings required would be justified. In this connection it must be remembered that lift makers voluntarily sacrifice 50 per cent of efficiency by making the worm-gear self-sustaining. This is a sacrifice of energy cost in order to ensure safety.

With regard to the life of ropes upon drum and sheave drives, if the drum and the sheave are of equal diameter the ropes will last longer on the drum. But this is very seldom the case in practice. Where one finds the drum introduced, it is usually in order that a higher-speed machine may be utilized, and consequently the drum is of smaller diameter than would be necessary for a traction sheave for the same job, and any advantage of drum over sheave as regards rope life is lost on account of the more acute bending of the rope.

The subject of d.c. motor field-windings is too large to deal with in this reply. For ordinary low-speed lifts a series winding is usually added to the shunt field and is automatically cut out when the motor reaches full speed. For higher-speed lifts many varieties of windings are employed.

Castor oil is found to be the best for gear boxes, because it is not easily pressed out from between the faces of the worm and wheel teeth which have to sustain great pressure. If the castor oil gums up it is because an insufficient quantity is employed and consequently the temperature-rise is too much.

The counter-weighting of lifts is dealt with in the paper. The usual practice for new lifts is 40 to 50 per cent of the maximum load plus the weight of the car, but an adjustment should be made after the average load has been ascertained in practice, as the correct balancing to the average load has an important effect upon the energy consumption.

I entirely agree with Mr. MacWhirter in his criticism of the practice of overhanging the driving sheave without an outer bearing. With regard to self-levelling, this has been dealt with in the paper.

The information given by Mr. Allan regarding a particular lift is extremely interesting, and it is very desirable that engineers should collect such information whenever opportunity occurs. It is upon data of this sort, in sufficient quantity, that lift engineers depend when advising as to a suitable lift equipment for a particular building.

DISCUSSION ON "ELECTRICITY IN MINES." *

DISCUSSION AT A JOINT MEETING OF THE WESTERN CENTRE OF THE INSTITUTION, THE SOUTH WALES INSTITUTE OF ENGINEERS, AND THE SOUTH WALES SECTION OF THE ASSOCIATION OF MINING ELECTRICAL ENGINEERS, AT CARDIFF, 12 JUNE, 1925.

Mr. W. O'Connor: Of all the data in the paper perhaps the most apt illustrations of the author's methods are those contained in the last two lantern slides. The first of these showed a site almost untouched in November 1923, and the second the same site with a colliery on its way to full development in the following year. Those who were told that they were wasting the very valuable resources of this country in burning coal at a much greater rate than they should, will derive great benefit from the paper. Many of us are inclined to think that some of the conditions laid down in the paper are utterly unattainable under present-day conditions, but there is much in the paper that we can use for the benefit of the concerns of which we are in charge.

Mr. D. Jenkins: Owing to the growth of our power supply undertakings and of generating stations in general, equalized electric winders have largely become unnecessary, and as a result the modern tendency is to omit the flywheels from Ward-Leonard sets. If my interpretation of it is correct, the present paper confirms this opinion. It is no doubt a step in the right direction, because from the point of view of the winding problem alone equalization brings no advantage. On the contrary, it increases both the capital and running costs of the equipment. Furthermore, as the number of electric winders connected to a system increases, the improving diversity factor will render equalization increasingly unnecessary. It seems likely, in fact, that within a comparatively few years the installation of an Ilgner equipment will become rare. By dispensing with the flywheel, speed variation of the motor-generator set becomes, of course, unnecessary, so that to install synchronous instead of induction driving motors seems a natural step to take. Nevertheless, the author is to be congratulated on being one of the first to break away from orthodox practice in this respect. I have always viewed the Stjernberg coefficient with suspicion. It would be exceedingly imprudent to decide, merely on the value obtained for this coefficient, whether for given conditions a Ward-Leonard or a straight induction-motor winder should be installed. A winder drive is affected by a large number of complex considerations which are not reducible to any mathematical formula. The coefficient in question, for instance, ignores entirely such considerations as those of economy, floor space, ease of control, etc. For these reasons I regret the coefficient has been put forward again. The present tendency is to install a straight induction-motor drive in preference to a Ward-Leonard set, on the ground of simplicity and cheapness. The modern practice of hoisting heavy loads at low speeds instead of light loads at high speeds has extended the field of economical operation of the induction-motor drive. Its great disadvantage as compared with a Ward-Leonard set is its comparative difficulty of economical control. The fact that its power input depends only on the torque and is independent of the speed inevitably means heavy losses during the acceleration period. Further losses take place during the retardation period because regenerative braking is impracticable. The only practicable means at present of reducing the former losses is to use multiple-speed motors or variable-speed gears or one or other of the many special methods of utilizing the slip energy regeneratively. All such means, however, involve complications, and their adequacy for the purpose in question is very doubtful. Has the author had experience with any of them? Judging from my own experience, reverse-current braking on induction-motor drives is by no means easy. The curves in Fig. 7 show that the braking torque producible by any given rotor circuit resistance depends upon the speed. It is difficult, therefore, to ascertain the correct position of the controller for a required braking effect. Furthermore, one cannot tell whether a forward or a backward motion of the controller lever is necessary to give a required variation of the braking torque, because this depends upon whether one is working on the one side or the other of the maximum on the torque curve. The result of these doubts and indecisions is that the winding engineman, for the sake of safety and precision, relies too much upon mechanical braking. Has the author found the same trouble? Of course, reverse-current braking involves a heavy duty on the controller, and it is clear this should be taken into consideration when designing the controller. I suspect that this point is frequently overlooked.

Mr. A. B. Muirhead: The Powell Duffryn Co. are placed in an unique position which admits of centralization of power being carried out to a much greater extent than appears to be practicable in other mining districts, and it is a matter of debate at the present time whether centralization on the same scale could be carried out with the same advantage in other areas. The lower grade of boiler fuel available in many of the coal-mining districts of Great Britain makes the splitting up of power stations desirable if only to reduce the cost of transporting the lower-grade fuel from the various pits to the central point, and the quantity of water to be pumped in many instances renders it desirable that there should be more than one power station available in an emergency. It will be found in many instances that, owing to the facilities available for the generation of power at low costs from these lower-grade fuels which

* Paper by Major E. I. David (see page 521).

will not pay to transport to any market, power can be obtained at sufficiently low cost and at reasonable efficiency with moderate steam pressures and superheat to enable the colliery owner to decide to use either electricity or compressed air underground as may best suit his mining conditions. The example of the Powell Duffryn Co. in these respects may be followed with advantage as far as the physical and economical conditions admit in each area.

Mr. F. Anslow : The author showed a lantern slide of a turbine plant coupled to two generators for supplying power to an electric winder, and remarked that he would not criticize this combination as it had only been in operation for a few months. As a matter of fact, three plants on this principle have been running for nearly 20 years, the only difference being that the generators, instead of being driven through gearing by a turbine, are driven direct by means of a high-speed engine. Indeed, these plants go a step further than those illustrated by the lantern slide, in that they have an additional generator included for the supply of current at a constant voltage, as distinct from the variable voltage of the Ward-Leonard sets. I am sure, therefore, that the author will be interested to know that the plant is in no way experimental, but is rather a revival of what has been done many years ago.

Captain A. C. Sparks : The paper refers more to electricity on the surface of mines than in mines, as the title would lead one to believe. It would be interesting to hear more about the old jockey pulley drive with modern improvements introduced by the author, as mentioned on page 522, unless he refers to the Lenix drive made by Messrs. Sulzer. With regard to the author's remarks on the subject of fan drives, when last in the United States I noticed that in one of the big coalfields it was the general practice to reduce the speed of the fans considerably during the light-load shifts, although it is not generally done in this country. This factor is largely decided by the mine manager, and I suggest might be further considered. In the Illinois coalfield, where the power required for the fan is, generally speaking, less than that required in South Wales, and the total units per ton are only about 1/10th of those required in South Wales, primarily owing to the natural facilities for coal getting, it is found desirable to do this. With reference to compressors, I feel that unless more consideration is given to the efficiency of the mechanical side the saving on the electrical side mentioned by the author may be lost. The low-load losses require to be carefully considered with the type of load experienced at collieries. The author briefly refers to pulverized fuel, stating on page 525 that " where fuels are available which cannot be burnt on any ordinary stokers, pulverizing is a feasible proposition." I doubt the accuracy of this statement without qualification, and do not feel that the subject is one that can be generalized upon at the present time. Whilst some time ago it was generally supposed that the feature of pulverizing was that the poorest fuels could be used commercially, it is interesting to note that the leading power houses using pulverized fuel in the United States are employing fuels having a calorific value about 12 500 B.Th.U. as received, which is by no means a poor class of fuel as we know it. As regards using low-grade fuels, the cost of pulverizing increases materially the lower the grade. I do not know what fuels the author has in mind, but abroad I have seen slurry, the residue from the water used for the washery, containing some 30 per cent moisture and 25 per cent ash, burnt on stokers, and also fuel containing 65 per cent ash. This latter fuel appeared to consist of small veins of coal in pieces of stone. Ignition was assisted in the former case, and combustion in the latter, by gas from coke ovens. The difficulty did not appear to be so much the burning of these fuels as the handling. With regard to winder gearing, I think that the question of using forced lubrication on the gearing, mentioned on page 526, is more a matter of gear design than of the size of the plant. I know one winding equipment with a motor of some 1 500 b.h.p. which has operated satisfactorily for several years without forced lubrication. With regard to the reversing switchgear, the author states on page 528 that apparently the blow-out coils were less effective when current and voltage are considerably out of phase. Power factor has a considerable influence on the breaking capacity of switchgear. With regard to the comparison of an Ilgner against a straight Ward-Leonard system, the author rightly points out that the figures given in Table 4 require adjustment for the difference between the winding schemes under the two cases cited. The figures might be materially changed on this account. A further point is that I believe that the Ilgner set mentioned was installed about 14 years ago, and is compared with a plant which was recently installed and which, I think, has not yet operated upon the coal-winding cycle. In this connection it may be interesting to note the progress in electric winding, and as this conference has had the privilege of visiting one small section of the Powell Duffryn Co.'s undertaking—and they are so associated with this progress—it may not be out of place to mention some of the work of that company, which, thanks to the enterprise of Mr. Hann and his family, is second to none in the efficient use of power, and has done so much to further development in the use of electricity at mines. In 1909 the first electric winding equipment was installed, an a.c. motor being used with direct drive. This type of equipment has limitations with which we are now all familiar. In 1911 an equipment of the Ward-Leonard-Ilgner type was installed, the generators being driven by an induction motor. At this time far less power was available than is the case to-day. In 1918 an a.c. geared winder was installed at a smaller cost than the Ilgner equipment, the power house equipment having materially increased at this time. In 1923 a Ward-Leonard equipment was installed, a synchronous motor being employed for driving the generators. This was of assistance in power factor correction, the need for which became so necessary as the extent of the undertaking increased.

Mr. R. G. Isaacs : I should be much obliged if the author would explain why it is that for pumping motors he uses induction motors almost entirely instead of synchronous motors.

Mr. H. Cotton (*communicated*) : The author's atti-

tude towards synchronous motors of the induction type has been criticized on several occasions, the paper apparently giving the impression that he is not too favourably inclined towards this kind of machine. This attitude may be due to the fact that some engineers have not realized that the induction type and salient-pole type of synchronous motor behave quite differently both during the starting period and during normal running. These differences provide a useful basis for comparison.

Starting.—The synchronous induction motor starts up exactly like an ordinary induction motor, its rotor being of orthodox construction except that it is wound for lower voltages than the rotors of plain induction motors: this has no influence on the starting torque. The exciter may be left in circuit during the whole of the starting period, but except when the slip is very small the pulsating torque produced by it has an average value of zero so that it does not contribute to the starting torque. The exciter is thus only called upon to pull the motor finally into step after the full

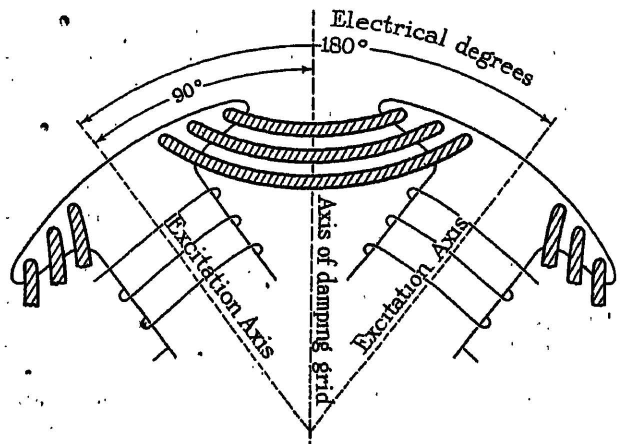

FIG. A.

induction-motor speed has been attained. Because of the above characteristics, the motor can start up against full-load torque, or even $1\frac{1}{2}$ times full-load torque, and can synchronize against these. The salient-pole motor is inherently a motor of low starting torque, and if starting torques comparable with those of the synchronous induction motor are required it is necessary to complicate the motor very considerably. The essential condition for a high starting torque is that the induced rotor currents should set up a rotating magnetic field whose amplitude should be as nearly constant as possible, that is, the field should be circular and not elliptical. This condition is not fulfilled when the motor is started up by the eddy currents induced in solid pole-shoes, or in damping grids of ordinary construction, since the induced currents in these cases are more in the nature of single-phase currents. The field set up by these currents has therefore a small rotating component but has a large alternating component, this latter being responsible for the sudden falling-off in starting torque when half synchronous speed has been attained. Several methods have been adopted to overcome this difficulty but unfortunately they all add to the complication of the machine, and incidentally to the cost. One method is to provide the pole-faces with a complete three-phase bar winding, the air-gap being reduced somewhat so that the motor has ordinary induction-motor starting characteristics. This is perhaps the ideal from the starting point of view, but it must be a very expensive construction, and even if one of the slip-rings is used by both exciting and starting windings the motor will require four slip-rings. The method adopted in the S.G.E. motor described by the author is very interesting, but there appear to be three serious objections to it. First the whole arrangement of the control appears to be unduly complicated, secondly the induced field will have a large alternating component, and thirdly, the damping windings which act in conjunction with the ordinary exciting windings to give the necessary starting torque will not act as dampers at all when the motor is running normally. The second objection follows from the essentially very different characteristics of the pole-face winding and exciting winding, even when the latter has its two halves connected in parallel. The motor must therefore suffer an appreciable drop in starting

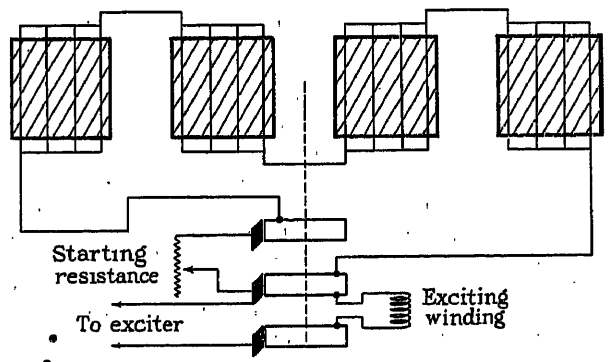

FIG. B.

torque when half speed is attained; and it will have a tendency to creep too slowly past this point, although probably this is not noticeable when driving a compressor, owing to the easy starting characteristics of this kind of load. The third objection is rather peculiar and it appears to have been overlooked previously. In order that a rotating field may be set up, the axis of the damping winding must be displaced 90 electrical degrees from the axis of the exciting winding, this latter acting as one phase, as shown in Fig. A. When the motor is running normally, the damper, to be effective, must be arranged with the centre of each grid coincident with the polar axis, whereas in the S.G.E. motor the grids are each 90° from the polar axis. In this position they will have practically no E.M.F. induced in them in the event of phase-swinging taking place during normal operation, and therefore as dampers they will be practically inoperative. The method of obtaining the necessary rotating field with the least complication is probably the two-phase arrangement shown in Fig. B. Here the orthodox damping grids

are joined together across the interpolar gaps, first on one side then on the other, so that the outside bars of the grids along with the connecting strips form a second phase displaced 90° from the polar axes. This phase is brought to two slip-rings, one of which is shared by the exciting windings, so that altogether only three rings are required as in the S.G.E. motor. Now in order that the two phases of this starting winding may have characteristics as nearly equal as possible it is necessary to have a large ratio of pole arc to pole pitch, and also to employ a narrow air-gap. But with such a construction the excessive magnetic leakage at the pole-tips and the effect of armature reaction, which would be large owing to the high value of the ratio (armature strength)/(field strength) occasioned by the use of a narrow gap, would practically wipe out the field set up by the second phase of the starting winding. This difficulty is overcome by employing a narrow gap at the pole face and by inserting non-magnetic liners between the pole cores and yoke. The total air-gap, from the point of view of the main field, is therefore a long one and the armature is magnetically weak in comparison with the field.

Running.—Although the synchronous induction motor shows up to advantage as regards starting conditions, the reverse is the case as regards normal running. Owing to the narrow air-gap of the induction type machine, it has a relatively strong armature which tends to produce instability if the load is at all fluctuating. On the other hand the very long air-gap of the salient-pole motor necessitates a magnetically strong field, and this renders the running of the motor very stable even with violently fluctuating loads. No better illustration of the stability of the salient-pole motor could be found than that afforded by the synchronous-motor-driven converter sets for the main winders at Llantrisant. In order to improve the operation of the synchronous induction motor in this respect it is usual to employ an air-gap somewhat longer than that used for a plain induction motor of the same size. Another method is to use an automatic regulator which adjusts the excitation to suit the magnitude of the load. Such a device should give a better utilization of the motor on fluctuating loads, since its use enables a smaller motor to be employed than would be possible if the motor ran with constant excitation.

General.—Except for machines with a small number of poles, say up to 6, a greater output for a given frame can be obtained with a salient-pole motor than with a synchronous induction motor, because the field ampere-turns do not become a limiting feature, and advantage can be taken of this to make use of an air-gap which is longer than that required for mechanical reasons alone. The induction-type machine is essentially a high-speed machine, whereas the salient-pole construction is more suited to medium and low speeds. On salient-pole machines the short-circuited winding chokes down the flux entering the poles at starting, thereby reducing the voltage across the slip-rings. This permits of a large number of turns per bobbin of the exciting winding, so that a standard excitation voltage can be used. When starting the induction type of motor the full voltage is switched on to the stator, and in consequence the field (rotor) turns must be kept low in order to prevent a very high voltage being set up across the slip-rings. In a plain induction motor of large size this voltage may be as high as 2 000 or 3 000 volts, obviously much too high for a circuit containing a small d.c. exciter, whether the exciter is left permanently excited or whether it is switched in by means of a manually operated change-over switch. This difference in the excitation voltage of the two types is very clearly illustrated by the following figures. The salient-pole synchronous motors of the Ward-Leonard converter sets at Llantrisant each have a capacity of 1 750 kVA, their excitation being 225 amperes at 65 volts. The fans at the same colliery are driven by synchronous induction motors each of 500 kVA capacity, the excitation for these being 370 amperes at 15–27·5 volts. In consequence of the low excitation voltage, the exciters of synchronous induction motors have to be built with very long commutators.

Although the author mentioned the use of turbo-speed compressors for long-distance transmission of compressed air, he did not refer to the driving of such compressors by electric motors. Presumably the compressors in use at present are all driven by steam turbines, as indicated on one of the lantern slides. What, in the author's opinion, is the most suitable type of electric motor for such a drive? The choice of motor appears to be the turbo-type synchronous motor, i.e. the motor having the same essential constructional features as the turbo-alternator, and the plain induction motor. The turbo-speed induction motor can, of course, be run as a synchronous induction motor, but it is more unstable when synchronized than the synchronous induction motor running at lower speeds, and would therefore probably not be considered. The turbo-speed induction motor has exceptionally good operating characteristics, its full-load power factor is high, and there is thus no necessity to employ a synchronous motor unless power-factor correction is a necessity. The cost of these motors is considerably less than that of synchronous motors of the turbo type. Possibly for very large outputs the synchronous motor would be preferable.

Major W. Roberts (*communicated*): About 12 months ago the author told me that his practice was to start motors up to 50 h.p. in size by switching them straight on the line. I notice that in a year his ideas on this subject, like many others, have progressed and he now talks of switching 150-h.p. motors straight on the line. In this respect I think he deals with bigger figures than anyone else, and the average colliery or supply undertaking would strongly object to this procedure. I take it that in his case it is only possible due to the size of his plant and the other apparatus connected to the lines. Can the author give any information as to the size of machine that can be started in this manner without harm to the remainder of the plant, as a percentage of the total generating plant and the load connected? Even with the special type of winding to which he refers, I take it that the current on starting is three or four times the normal

full-load current, and as this presumably means that his overload releases are inoperative during the starting process, does he not think it a disadvantage to have machines of such large size coupled directly to his supply without any protecting device as they (presumably) are with a two-position starter? In describing one of the lantern slides the author gives 23 or 24 per cent as the starting torque of a compressor with an unloading device. Can he state what this figure would be for ordinary reciprocating compressors without unloading device? He mentioned, I think, that on one job the starting current was approximately equal to normal full-load current, but this figure appears to me to be somewhat on the low side, and I shall be glad to know if it is a figure that he has consistently found in practice.

Major E. I. David (*in reply*): Mr. Jenkins is suspicious of the Stjernberg coefficient. As I have previously stated, it must be used with circumspection. It is useful as a first approximation for eliminating the extremes. Nothing but a complete examination, by experienced engineers, of all the complex factors can finally settle the best type for each particular purpose. Reverse-current braking is far simpler than would appear from the curves in Fig. 7. To attain creeping speed, the resistance in the controller is such that a movement away from the central position of the lever through a limited range increases the braking torque at all speeds. In the large a.c. winders described (see Fig. 6) the mechanical brakes are only used to effect the final braking and to hold the drum stationary; all main deceleration and weight-lowering is done by reverse current. The heating effect of this must be calculated and the controller and the motor rotor designed accordingly.

Mr. Muirhead rightly refers to some of the factors which have to be considered in the power supply for a group of collieries. In the case mentioned there are six main power stations all interlinked electrically, utilizing gas and low-pressure, high-pressure and extra-high-pressure steam. Duff coal is used almost exclusively for steam generation.

Mr. Anslow's reference to the 20-year-old steam-driven Ward-Leonard sets is most interesting and gives rise to the question: Why have more plants of this type not been installed?

In reply to Captain Sparks, the drives referred to are Lenix drives (see also page 565). I would refer this speaker to the figures given on page 524 for the light-load losses in the high-speed vertical-type compressors. The mechanical efficiency of these machines is exceptionally high. The fuels I refer to as difficult to burn on ordinary stokers are low-volatile washery slurries and froth flotation coals, both already very fine and easily pulverized and of high calorific value. Certain gear-makers do not insist on forced lubrication, whilst others, using similar tooth pressures, do. I prefer to be safe and fit sprays in all cases. Captain Sparks may be interested to know that the old direct-coupled 1909 winder motor with a new drum is still doing 100 per cent overload every day in a new pit. The power units available in 1911 were much smaller and equalization was necessary. A 2 500-h.p. winder now bears the same relation to the power units as a 250-h.p. haulage did then.

In connection with Mr. Isaacs's remarks, I would refer him to page 522.

Mr. Cotton's valuable contribution clearly describes the relative merits of the salient-pole and synchronous induction-type synchronous motors. His conclusions agree with mine, namely, that for low-starting-torque low-speed high-efficiency drives such as compressors, the salient-pole machine is preferable and usually cheaper; and that for high-speed high-starting-torque drives with slight overloads such as ventilating fans the synchronous induction motor is preferable. High efficiency is essential, and the synchronous induction motor can be designed for efficiencies nearly as high as those of salient-pole machines for speeds of 600 r.p.m. upwards. For large high-speed motor-generator sets salient-pole machines are cheaper, more stable, more robust and slightly more efficient, whilst their starting torque is ample and their excitation voltage more reasonable. Provided high efficiency can be obtained, I prefer for turbo-compressor drives a plain induction motor, because of its stability and also because the load variations are so extreme that it would be difficult to prevent violent power-factor fluctuation in a salient-pole or synchronous induction motor. The speed of most turbo-compressors of 7 500 to 15 000 cubic feet per minute capacity is from 4 000 to 6 000 r.p.m. Gearing is therefore necessary and a normal machine of 600 to 1 000 r.p.m. is cheaper and more efficient than a machine of the turbo type. Speed variation of 10 to 15 per cent would be a great advantage.

In reply to Major Roberts, switching a 150-h.p. Boucherot-type motor on the line produces a kick of 3 to 4 times full-load current, falling rapidly to $1\frac{1}{2}$ times, but this is small compared with the starting current of a 1 600-h.p. a.c. winder motor. The two overload trips have oil dash-pot time-lags and are set for 75 per cent overload, but there is an instantaneous earth-leakage trip. Induction-motor-driven compressors up to a capacity of 3 000 cubic feet per minute are frequently started up without unloading against full receiver pressure and, when cold, take up to 150 per cent of full-load current, but it is preferable to use the unloading device.

DISCUSSION ON "THE DRIVE OF POWER STATION AUXILIARIES."*

WESTERN CENTRE, AT CARDIFF, 2 MARCH, 1925.

Mr. J. W. Burr: Years ago we did not worry very much about our auxiliaries. If they failed it simply meant running the engine to atmosphere and coupling up an extra boiler. To-day, with turbine units, the failure of any part of the auxiliary plant entails shutting down quickly. Our auxiliaries, therefore, must be reliable, as continuity of supply is essential. The authors state that half an hour's interruption may be attended with disorganization at the works. In my district a much shorter interruption is sufficient to cause great disorganization at the works and collieries, particularly the latter. The importance of the duplication of auxiliaries depends, in my view, upon the number of sets running at one time. For example, if four sets were running it would, obviously, not be so necessary to duplicate the auxiliaries as in the event of the load being taken by one set. Referring to the boiler feed-pumps, I prefer to drive half by steam and half by electricity, and I suggest that if certain of the auxiliaries were driven by d.c. motors in connection with a battery it would not be necessary to install a house set, as suggested by the author. As regards injectors, I think it is common practice to fit these in duplicate, each dealing with 60 per cent of the steam at maximum load.

Mr. F. H. Corson: I should like to associate myself with the view expressed by Mr. Burr as to the outstanding importance of reliability in public electricity supply, even, if necessary, at some sacrifice of cheapness. Economy of generation is governed principally by the main generating sets, but reliability is perhaps more closely dependent upon the arrangement and operation of their auxiliary machinery. I have often been accused of unduly stressing the importance of continuity of supply, and it may be of some interest to mention a few only of the results of a shut-down some 12 months ago, the actual duration of which was only 3 minutes. The machinery of a flour mill was stopped for about 3 hours, a week's output at an artificial silk factory was spoilt, and a charge of ice at an ice factory was lost because a man had such confidence in our reliability as to leave his plant running unattended. At a chemical works some delicate operations were interrupted and possibly ruined altogether, and similar results occurred at a milk sterilizing and pasteurizing depot. I am therefore very glad that the authors have made this the keynote of their paper. I have recently had to consider the question of effective stand-by provision to auxiliary machinery, and have approached it from two distinct points of view: first that of the failure of an important auxiliary, as, for example, a circulating pump the repair of which may take some time, and where the running economy of the stand-by provision must be equal to that of the machinery it replaces; and secondly that of a complete shut-down where running economy is of no importance, and where the simplest and quickest means of recovery must be provided, regardless altogether of its economy of performance. In my opinion the authors acted wisely in confining themselves to a sort of abstract analysis in their investigation of the operation of auxiliaries, and in refraining from making any specific recommendations.

Mr. J. E. Teasdel: It certainly does seem strange to talk at this date about the necessity for a continuous supply. I thought it was generally agreed that this was of paramount importance and overshadowed all questions of cost. There may, however, be extremes in the matter of duplicated auxiliaries, etc. I have known a case in which every engine had two steam pipes to a breeches pipe. After the plant had been running for 20 years the coverings began to fall off the duplicates and they were sold for scrap as they had never been called into use. It would appear to be more necessary to duplicate mains rather than steam pipes, because in these days there is probably more trouble arising outside the station than inside.

Mr. A. J. Newman: I should like to endorse all that Mr. Burr and other speakers have said as to the paramount importance of reliability. Take the case of a flour mill deriving its power from a local supply undertaking. A variation of frequency even may upset their mill operations for an hour or more and interfere considerably with their output. There is also the case of chemical works, to which reference has already been made. It has been our modern practice to install steam ejectors in duplicate for air-extraction purposes. We have not, however, yet reached the stage of having a stand-by for the circulating-pump system, but it is at the present time receiving my serious consideration. I am rather in favour of letting a turbine float on the same shaft as the motor, with an automatic change-over device. I should like to know what the authors think of such an arrangement. With regard to the extraction pump, our practice is to use three-phase alternating current taken from the main busbars for our engine room auxiliary supply and to have d.c. auxiliaries for boiler-house purposes, chiefly because of the desirability of having speed regulation in the latter case. The damage caused by a large turbine going to atmosphere should be avoided at all costs. There are occasions, however, when one may be obliged to go to extreme measures. One of these occasions actually occurred at our generating station. We had a 4 000-kW set running on atmosphere for considerable periods to carry our load over the Christmas peak. As to auxiliaries in the boiler house, our practice is to have steam feed-pumps. We use turbines for this purpose, chiefly because they take the form of feed-water heaters. They are close to the

* Paper by Messrs. L. Breach and H. Midgley (see vol. 61, p. 829, and vol. 62, p. 243).

hotwells and are quite satisfactory and reliable appliances.

Mr. O. S. Hosgood: The list of alternative schemes given in the paper is very useful. A special d.c. generator on the end of the main turbo-alternator shaft would, in my opinion, be a danger. If the alternator set is shut down due to a breakdown, then the auxiliary d.c. set would of course be useless. It is wiser to have the auxiliaries away from the main shaft and have an independent drive. As to having a d.c. plant for the boiler-house auxiliaries, should the d.c. plant break down one must have an alternative scheme to get the auxiliaries going again, because the boiler house is of great importance. Then there is the question of feed pumps in the boiler house. I quite agree with Mr. Burr that electrically-driven pumps should be duplicated.

Mr. P. J. Plevin: I believe that in one American station each of the four or five units it contains is provided with its own house set. These house sets generate current for driving auxiliaries. Each is fitted with a jet condenser, the cooling water for which is the condensate from the main condensers, which have a vacuum of about 29 in., the temperature of the condensate being about 80° F. The vacuum in the jet condenser is, I believe, about 25 in., and the temperature of the water extracted is about 130° F. The water extracted (which includes the condensed steam from the house turbine) is therefore passed into the economizer above the temperature at which condensation takes place on the tubes. Each main and house set is an independent unit. The system has the objection that if the house set breaks down the main set is shut down also. Another objection is that fluctuation in load on the main set means a corresponding variation in the quantity and temperature of the cooling water supply to the condenser of the house turbine, and therefore a variation in the supply of power to auxiliaries. The scheme, however, impressed me as being simple, and I should be glad to have any details of its performance which the authors can supply. The question of reliability has been stressed, quite rightly, by every speaker in the discussion. In earlier days not sufficient attention was paid to matters such as motor control-gear. Very often cheap designs were accepted that were suited only to ordinary commercial work, without consideration as to their relationship to the complete set in respect of immunity from breakdown. Such was also the case with regard to auxiliary turbines. When the turbine drive for auxiliaries first came into favour, many cheap foreign machines of quite unsuitable design were used. In many cases due attention was not paid to the steam connections. It was thought that all that was necessary was simply to take a branch from the main steam pipe to the turbine, and such factors as drainage and provision for expansion were frequently ignored. This is probably one reason why the steam turbine for auxiliary drives fell into discredit. There is one other matter which should be borne in mind, and to which I do not think the authors have alluded. I refer to the layout of auxiliary plant. In older layouts especially, auxiliaries were frequently placed in any position which provided floor space, entirely without regard to accessibility for inspection and overhauling and to the fact that their satisfactory performance is just as vital as that of the main sets. This, of course, is wrong, and in my opinion the proper location and installation of auxiliaries is just as important as that of the main plant.

Mr. R. Roper: We have recently installed a house turbine on similar lines to that mentioned by Mr. Plevin. This unit is complete with turbine, alternator and jet condenser. The condensate from the main units is utilized as cooling water for the jet condenser on this small house turbine. The water from this jet condenser is delivered to hotwells in the boiler house, and from thence pumped into head tanks. The exhaust steam from the head pumps and the feed-pumps still further heats the head tanks, and the temperatures can be taken as 150° F. for the hotwell and 200° F.–220° F. for the head tanks. This temperature can be varied by adjusting the load on the house set by means of change-over switches on the duplicate auxiliary busbars. The efficiency of this house turbine is not of such prime importance as the greatest reliability of service. With regard to our circulating water, we have a large circulating pump of 530 h.p. delivering 18 500 gallons per minute into one common header pipe, and from this pipe we take a supply of circulating water for the various condensers. I much prefer steam-driven to electrically-driven boiler feed-pumps. The exhaust steam from the steam-driven feed-pump can be passed through evaporators, and by so doing we are able to obtain a large percentage of supplementary feed for our boilers. This method is, I think, quite as economical as the electrically-driven feed-pump; in addition, should any trouble be experienced on main generating units the steam pump can always be relied on to feed the boilers. The house turbine runs at 5 000 r.p.m., and this is reduced through gearing to the generator which runs at 500 r.p.m. We are also doing without economizers on our new boiler plant, using air heaters instead.

Mr. W. Holley: The moral to be drawn from both paper and discussion appears to be that we need better auxiliaries. Every operating engineer knows that some of his plant rarely breaks down and that some is more troublesome. If all were as good as the best there would be very few breakdowns. When trouble occurs it is nearly always from some small cause such as a contact too small for its work or a brush difficult to adjust and therefore to keep in order. I suggest that manufacturers should look more into these details—I am sure every operating engineer would gladly assist them. Auxiliary plant is too often installed in awkward positions and consequently is not cleaned and properly examined because of the difficulty of getting all round it.

Mr. R. Hodge: Referring to Mr. Holley's remarks as to the class of apparatus supplied for power station auxiliary control in the shape of contacts, etc., and speaking as a representative of a manufacturing firm, I should like to say that it is the manufacturer's endeavour at all times to provide apparatus of such a quality as will ensure continuity of supply. In connection with the size of contacts, etc., it must always be borne in mind that the financial aspect more often than not enters into this point. If the buyer is prepared to pay a reasonable price he can always be assured

that reputable manufacturers will supply him with an article in which the contacts and other wearing parts are of ample capacity and dimensions to withstand the conditions of service. The question of buying a cheap, if not the cheapest, type of control gear for use in conjunction with the control of power station auxiliaries is very much to be deprecated, especially when one realizes that the cheap control gear may form the one weak link in the chain of continuity of supply.

Mr. H. Wilson: We in the Post Office Engineering Department cordially appreciate, and are ready to applaud, every effort made by power station engineers to ensure that we shall have absolute continuity of service in all circumstances. In practically every telephone exchange in the country we provide duplicate power plant to guard against a failure in the public supply, and at the moment we are installing an 80-h.p. oil engine in a neighbouring town as a stand-by against such a failure. We are naturally desirous that, in general, any duplicate plant necessary should be provided in the power stations and not in Post Offices.

Mr. T. Stretton: This is the day of interlinking of power stations. I assume that we are dealing chiefly with new power stations, and there are very few power station sites in this country where an alternative supply is not available. Every effort should, I think, be made to learn whether an alternative supply is available, and the auxiliaries arranged accordingly. Mr. Wilson mentioned that oil engines were being installed as a stand-by. In a recent lecture before the South Wales Institute of Engineers, Mr. Clark, the consulting engineer to the municipalities of Johannesburg and Pretoria, described a new power station at Pretoria and mentioned that the stand-by plant which he had installed was a petrol engine and generator.

Mr. C. T. Allan: Mr. Plevin has called attention to one of the most important points, namely, reliability. Cases of failure are sometimes due to inadequate protective gear on the switchgear controlling the auxiliary. Sometimes this is too complicated, and what is always needed is simplicity to reduce delay after stoppage.

Mr. T. H. Wood: I think that the authors pass too lightly over the question of the most efficient drive. During this discussion at least two central-station engineers have advocated turbine-driven feed-pumps. I take it that they prefer this type of drive because reliability is of paramount importance in feeding the boilers. This being so, I think that the most serviceable drive would be the one described by Mr. Newman, which incorporates the alternative motor or turbine drive. The normal drive in this case is the steam turbine, because, provided the exhaust steam can be utilized in heating the feed water, this is the most efficient, giving an overall efficiency of about 90 per cent. On the other hand, in the case of the electric drive the efficiency taken over the same range, that is, from steam supplied at the main generator to the power given out at the auxiliary coupling, would only be about 20 per cent. Of course this difference in efficiency is accounted for by the fact that in the first case the whole of the useful and latent heat in the steam is utilized, partly in pumping the water and partly in heating the feed water, whereas in the second case the latent heat is lost, being rejected into the condenser cooling water in the process of converting the steam into electrical units in the main generator.

Mr. W. Nairn: On page 830 (vol. 61) the authors state: "Unless the flow of circulating water through the condenser tubes is due, in whole or in part, to gravity (a highly desirable state of affairs which can rarely be obtained except in hilly countries), it is evident that a stoppage of the circulating water pump will mean a stoppage of the flow of circulating water." Electrical engineers are often criticized for not making more use of water power for generating electricity, and the authors' comment is a reply to such criticism, as the fact is that not a station of any size in this country has been able to command sufficient water power to get a gravity flow for condensing purposes. If such a supply could be obtained either for gravity circulation or for driving the station auxiliaries it would be a godsend to station engineers.

[The authors' replies to the earlier discussions on the paper (see vol. 61, p. 861, and vol. 62, p. 246) cover the points raised in this discussion.]

FUSES AND FUSIBLE CUT-OUTS.*

By P. G. ASHLEY, B.Sc.(Eng.), Student.

(ABSTRACT *of paper read before* NORTH-EASTERN STUDENTS' SECTION, *20th February,* 1925.)

SUMMARY.

The paper briefly reviews the history of the development of fusible cut-outs, and proceeds to discuss in turn the various factors affecting the design and behaviour of wire and plate fuses in air.

The main features of fuse wires in oil are considered and also how their design and behaviour compare with those of fuses in air.

Various types of enclosed and semi-enclosed cut-outs are described, as well as oil-immersed switch-fuses. The theoretical aspect of the mechanism of fusing is summarized in Appendix 1, and the present position as to standardization in Appendix 2.

INTRODUCTION.

In the early days of electricity supply the dangers of short-circuits were not fully realized, and if the station operator could not open his knife switches in time a considerable part of the mains had to be replaced. The idea was conceived of reducing the section of the conductor in one part of the circuit so as to cheapen replacement and reduce the destructive effects of a short-circuit. As the benefits of this practice were realized, improvements were effected in the amount of conductor to be replaced and the means of replacing it, and the fusible cut-out as we know it to-day began to take form.

HISTORICAL.

In 1879 the late Prof. S. P. Thompson invented a cut-out consisting of two iron wires connected by a ball of lead. Under abnormal conditions the lead melted and the wires flew apart. In 1883 Boys and Cunyngham patented a safety fuse with springs; and Kelvin's fuse, which consisted of two pieces of springy copper soldered together by means of a low-melting-point alloy, was produced in 1884. Cockburn brought out his weighted fuse in 1887, and other special forms such as cartridge and Edison plug fuses soon followed. In those days resinous wood was frequently used for the bases, and as a result of these bases catching fire the fuses were often in disrepute. The risk of fire, although not yet entirely eliminated, is to-day considerably reduced by the use of porcelain, slate, and other non-inflammable insulating materials.

DEFINITIONS.

The following are the most important definitions to be noted in connection with the subject of fuses:—

"Cut-out." A device for protecting circuits or apparatus from overload by means of the fusion of a specially designed part.

"Fuse link." That part of the cut-out which is designed to open the circuit by fusing or melting.

"Protected cut-out." A cut-out in which provision is made for protecting the operator from any dangerous effects of operation.

"Rated carrying current." The maximum current the apparatus will carry under prescribed conditions.

"Fusing current." The actual current at which the metallic circuit is broken.

"Minimum fusing current." The minimum current which will, under prescribed conditions, cause the fuse link to melt.

"Fusing factor." The ratio of minimum fusing current to rated carrying current.

MINIMUM FUSING CURRENT.

One of the most important characteristics of a fuse link is its minimum fusing current, which is closely associated with the rated carrying current. Such terms as "normal fusing current" are confusing, and it is better to use the word "minimum" or else to refer to the time of fusing at a definite current value.

The two accepted methods of determining the minimum fusing current are (1) by plotting a curve of fusing current against time and (2) by steadily increasing the current until the fuse melts. In the former case the full current is allowed to flow through the fuse and the time of fusing is noted; whilst in the latter case the fuse is allowed to attain a steady temperature before the next increment of current is applied. Method (1) is the quicker and simpler of the two and the one most commonly employed.

At supply frequencies it is immaterial whether the fuse link is tested with alternating or direct current, provided that only commercial accuracy is required. Tests by the author show definitely, however, that the minimum fusing current with alternating current is lower than with direct current.

MECHANISM OF FUSING.

Fundamentally, while $0 \cdot 24\ I^2R$ calories are being generated each second in the fuse link, dissipation is taking place by conduction, convection and radiation. Neglecting deterioration, any current at which the heat dissipated is equal to the heat generated is a safe continuous rating for the fuse link. It is almost impossible to determine the safe rating theoretically, owing to the difficulty of determining the loss due to the factors of dissipation. Appendix 1 shows the development of various formulæ for determining the minimum fusing current. These formulæ throw interesting light on the mathematical side of the question, but

* A Students' Premium was awarded by the Council for this paper, and it is the practice of the Council in such cases to publish the paper, in full or in abstract, in the *Journal*.

in practice a judicious compromise between theoretical formulæ and reliable test-figures will usually give the required information.

Fuses in Air.

Most of the original investigations on fuse links in air were carried out by the late Sir William Preece. Improvements on his formula have been dealt with by Schwartz and James,* and their paper remains almost a standard work of reference.

Factors Affecting Fusing Current.

The chief factors concerned in determining the fusing current of a fuse link are :—

(1) Diameter of wire, or breadth and thickness of a plate fuse.
(2) Material.
(3) Length of fuse and mass of terminals.
(4) Environment and position.
(5) Time of current-flow.
(6) Whether fuse is in tension or not.

Diameter of Wire.—Assuming all other factors to be fixed, Preece gives $I = ad^{1 \cdot 5}$, where I is the minimum fusing current, d is the diameter of the wire, and a is a constant having the following values when d is expressed in millimetres : Tin, 12·8 ; lead, 10·8 ; copper, 80. Table 1 is calculated from this formula.

Table 1.

Nearest S.W.G. for Given Minimum Fusing Current.

Current	Tin	Lead	Copper
amps.	S.W.G.	S.W.G.	S.W.G.
1	37	35	47
2	31	30	43
3	28	27	41
5	25	23	38
10	21	20	33
15	19	18	30
20	17	17	28
25	16	15	26
30	15	14	25
40	14	13	23
50	13	—	21
60	—	—	20
80	—	—	19
100	—	—	18
160	—	—	16
200	—	—	15

Schwartz and James give the following modifications of Preece's formula :—

When fusing current lies between 1 and 10 amps.

$$I = K_1 d^{1 \cdot 195}$$

When fusing current lies between 10 and 100 amps.

$$I = K_2 d^{1 \cdot 403}$$

* *Journal I.E.E.*, 1905, vol. 35, p. 364.

Table 2 shows how these formulæ compare with Preece's formula.

Table 2.

Comparison of Indices and Constants for Formula of Preece and of Schwartz and James Formulæ.

Material	Range of fusing current, amps.	Schwartz and James		Preece	
		Index	Constant	Index	Constant
Copper	1 to 10	1·195	52·4	1·5	80
	10 to 100	1·403	69·9		
Tin	1 to 10	1·195	10·8	1·5	12·8
	10 to 100	1·403	11·5		

Material.—With tin and lead, owing to their high resistivity compared with that of copper and silver, the size of wire required to carry a given current is greater. This reduces the safety, as a greater amount of metal has to be volatilized when the fuse blows. Aluminium and zinc, although almost non-arcing metals, have the disadvantage of being mechanically weak. A peculiar disadvantage of aluminium is that when the wire is carrying load a skin of oxide or carbonate forms which is sufficiently tough to retain the molten core of the metal. This phenomenon is associated to a lesser degree with tin and lead wires. It was first observed by Cockburn in 1887, and that was why he weighted his wires. The oxide-skin effect is not so noticeable with large wires, as the formation of the skin prevents further oxidation or carbonization. It is probable that the thickness of the skin is constant for all sizes of wire, and therefore has less effect on the larger diameters. Copper is the most common metal used for fuse wires owing to its high conductivity and comparatively low watt loss ; it is fairly "clean" in fusing, and is mechanically strong, cheap, and easily obtained.

Three special forms of fuse links have been placed on the market within recent years, viz. bi-metal fuse wire, the "Aeroflex" fuse element, and the "Zenal" fuse element. All of these are designed on substantially the same principle, i.e. they consist of a low-melting-point metal of comparatively low electrical conductivity in parallel with a metal of high conductivity and higher melting point. On overload the alloy melts fairly slowly, is released, and falls away from the fuse link, leaving the copper alone in circuit. The section of the copper is so proportioned that it will not alone carry the increased current, and the overload is therefore cut off by the copper. The general effect of this principle is that the fuse link can be run at a current value very near to its minimum fusing current, the generated heat being mainly dissipated by the low-melting-point alloy. When the alloy has fallen away, however, the actual work of opening the circuit is carried out cleanly and quietly by the copper.

Length of fuse link.—As shown in Appendix 1, in developing the Preece formula the length of fuse link does not enter into the theoretical determination of

the minimum fusing current. Actually, the effect of this factor is closely associated with the mass of the terminals. To make a true comparison between the minimum fusing current of a long length and of a short length of wire the relation between the length of wire and the mass of the terminals should be kept constant. This condition is practically impossible to obtain. If the mass of the terminals is kept constant the minimum fusing current is proportional to the reciprocal of the length. So far as a short-circuit is concerned, it is only necessary to make the distance between the terminals such that an arc cannot be maintained when the cut-out is subjected to the worst conditions which it will have to encounter.

Environment and position.—Environment plays a large part in deciding the minimum fusing current and therefore the rated carrying current of the fuse link. Types of cut-outs range from open, in which the fuse link is quite bare with a large volume of air round it, to totally enclosed cartridges in which the fuse link is contained in a closed tube packed with some form of insulating powder. The difference caused by these extreme conditions will be appreciated and it will be seen that no theoretical estimate can be made of this effect.

Tension.—The object of employing spring tension is to give the cut-out a higher breaking capacity; the reduction in minimum fusing current which also results is very often undesirable. It is unlikely that Ferranti in his early oil fuse adopted spring tension to increase the breaking capacity, as it was little understood in those days: it is more probable that he found it a convenient means of preventing flash-over between the terminals.

Plate Fuses.

Plate fuses allow more scope in design than wire fuses, owing to the fact that considerable variations in minimum fusing current can be obtained by suitably proportioning the breadth and thickness of the plate. In addition, for the same volume of metal a plate fuse will carry much more current than a wire fuse, owing to the larger cooling surface.

Watt Loss and Fusing Factor.

The watt loss at normal load depends upon the fusing factor, i.e. the ratio of minimum fusing current to normal load, or rated carrying current. A fusing factor of 2 is frequently asked for by supply undertakings, but it is very doubtful whether this factor is suitable. A factor of 3 is preferable, as this considerably reduces troubles due to deterioration as a result of oxidation. A large fusing factor means a high overload setting, but low watt loss and a minimum of oxidation troubles. A small fusing factor gives definite action for light overloads, but is liable to give trouble due to heating.

Fuse Links in Oil.

In the opinion of Schwartz and James no fuse wire should be used in actual contact with oil. Despite this opinion, oil-immersed fuses are giving satisfactory service in all parts of the country. The same development has taken place as with circuit breakers: the oil-immersed circuit breaker is the natural outcome of the need for apparatus capable of breaking large currents at high voltages, and the oil-immersed fuse is the outcome of the same need.

The previous remarks regarding fuse links in air apply equally to fuse links in oil. Copper, tin, lead and bi-metal fuse links have been successfully used. The watt loss is about four times the loss for the same rating in air, this being due to the fact that increased cooling allows a higher current density to be employed. Tests show that the minimum fusing current increases as the head of oil over the fuse is increased, but actual figures are not at the moment available. The ratio of minimum fusing current in oil to minimum fusing current in air for a precisely similar arrangement of fuse wire and terminals depends upon the head of oil, but is of the order of 3 to 3·5 for a 5-inch head.

Types of Fusible Cut-outs.

Fusible cut-outs as a class may be divided into (1) open, (2) semi-enclosed, and (3) totally enclosed, of which the open type is now practically extinct. The semi-enclosed type usually takes the form of an insulating tube open at the ends, the fuse link passing down the centre of the tube; whilst the totally enclosed type consists of a tube completely filled with an insulating powder through which the fuse link passes. This filling material rapidly cools the generated gases by forcing them into the interstices of the powder, and thus effectually smothers the arc.

Potential Transformer Fuses.

These are designed for the express purpose of protecting the system from the effects of a short-circuit on the high-tension side of the potential transformer. It is generally recognized that it is necessary to use a resistance in series with these fuses, the value of the resistance depending upon the short-circuit kVA at that point. In metal-clad gear where the saving of space is important, one manufacturer has embodied this resistance in the fuse. This fuse is of the enclosed type and consists of a small-gauge wire of special alloy, the tube being filled with marble dust. This wire is itself of high resistance, and with extra-high-voltage gear a further saving of space is achieved by winding the wire spirally on an insulating core.

Schwietzer and Conrad Fuse.

The "S. & C.," "Empire," or carbon tetrachloride fuse consists of a glass tube filled with carbon tetrachloride containing a spiral spring the lower end of which is connected to the bottom ferrule. The upper end of the spring is attached to the fuse, which passes through a cork and is connected to the top ferrule. At the top of the spring and just below the cork is a funnel-shaped liquid-director. Melting of the fuse wire releases the spring, which then draws the moving terminal down to the bottom of the tube. Simultaneously with the introduction of this large gap the liquid extinguishes the arc, the rapidity of its action being accelerated by the liquid-director, which forces the liquid directly on to the moving terminal.

Switch-Fuses.

In this apparatus the blade or blades of an ordinary knife switch are replaced by fuses. The modern development for high-tension work is the oil-immersed switch-fuse, many of which are in use all over the country at voltages from 660 to 33 000. These switch-fuses are primarily intended as a cheap piece of apparatus for controlling a tee from a high-tension line in places where a circuit breaker is prohibitive. The fuse links are held under spring tension in the middle of a fairly large volume of oil and under a head of oil depending upon such factors as working voltage and requisite breaking capacity. Being totally enclosed and metal-clad these switch fuses can be safely used out-of-doors without any special covering. They may be used as single units or coupled together to form a complete panel. In addition, they can be arranged to line up with existing metal-clad switchgear, and arrangements are made for fitting current transformers for metering or protection purposes.

Standardization.

Efforts have been made from time to time to put cut-outs into one or more standard forms, and although we have a British Standard Specification (No. 88) it is rarely that a purchaser specifies that the apparatus which he is buying shall comply with this Specification. The Americans have gone very much further, the Specification of the National Electric Code being a thoroughly sound one and in constant use.

Mr. H. W. Kefford * says: "If we would foster the popularity of electrical applications and the prosperity of the industry we must create and maintain confidence in the safety, reliability, and convenience of electrical power by every possible means . . . the standardization of fuse design would undoubtedly conduce to economy in manufacture and result finally in a reduction of cost."

In conclusion, the author particularly wishes to thank Mr. H. W. Clothier for his helpful criticism of the paper in its draft stage.

APPENDIX 1.

Mechanism of Fusing.

The fundamental relationship up to the point of fusion of the wire is :—

Heat generated = Heat dissipated by conduction, convection and radiation.

By Newton's law of cooling the loss of heat per second is proportional to the difference between the temperature of the wire and the temperature of the enclosure, and experiment shows it to be proportional to the surface area of the wire. The gain of heat per second is proportional to I^2R, that is

$$\text{Heat generated} = 0\cdot 24I^2R, \quad \text{or} \quad 0\cdot 24I^2\rho l/\tfrac{1}{4}\pi d^2$$

where I = current flowing ;

ρ = specific resistance of copper ;

l and d = length and diameter of wire respectively.

$$\text{Heat dissipated} = e\pi dlT$$

where e is the emissivity of the material, i.e. the heat in calories radiated in one second from unit area when the temperature difference is 1 deg. C. ;

and T is the temperature difference ;

Then $$e\pi dlT = 0\cdot 24I^2\rho l/\tfrac{1}{4}\pi d^2$$

and $$T = 0\cdot 097\frac{I^2\rho}{ed^3} \quad \text{or} \quad I = d^{1\cdot 5}\sqrt{\left(\frac{Te}{0\cdot 097\rho}\right)}$$

This is the general form of Preece's formula, the expression under the root sign being reduced to one constant in the final form.

Example.—Copper fuse wires in air.

We have: Melting temperature of copper = 1 080° C.; air temperature (assumed) = 20° C., whence $T = 1\,060$; e for copper = $0\cdot 00035$; $\rho = 7 \times 10^7$ ohms per cm³.

This gives the minimum fusing current for

No. 18 S.W.G. = 97 amps.
No. 24 S.W.G. = 33·8 amps.
No. 30 S.W.G. = 12·7 amps. (cf. Table 1).

W. Wilson, in an article on time-element fuses * gives

$$\frac{1}{I^2} = \frac{a}{T_f}(1 - \epsilon^{-t/\tau})$$

where I = current flowing ;

$a = 0\cdot 24R/(Ae)$;

e = emissivity ;

A = cooling surface ;

R = resistance of fuse link ;

S = specific heat of material ;

$\tau = MS/(2\pi rle)$;

M = mass of fuse link ;

r = radius of wire ;

l = length of wire ;

t = time ;

T_f = fusing temperature.

It will be seen that for the minimum fusing current, t = infinity and $\epsilon^{-t/\tau}$ = zero. The equation therefore becomes

$$\frac{1}{I^2} = \frac{a}{T_f}$$

Example.—Copper fuse wires in air.

Minimum fusing current for

No. 18 S.W.G. = 98·5 amps.
No. 24 S.W.G. = 34·14 amps.
No. 30 S.W.G. = 12·88 amps. (cf. Table 1).

For lead wires C. P. Feldman † gives $I^2L^{0\cdot 5} = Ad^3$, where L and d are the length and diameter respectively in mm, and A has the value 1 350 for 150-gramme terminals, and 1 000 for 30—gramme terminals.

Example.—Lead wire in air, No. 18 S.W.G. ; length $2\tfrac{1}{2}$ in. ; terminals 30 grammes. Minimum fusing current = 14·7 amps. (cf. Table 1).

For aluminium plate fuses Schwartz and James ‡ give $I = K(b - 0\cdot 035)\,(t - 0\cdot 0024)$, where b and t are

* H. W. Kefford: "Standardization of Fuses," *Journal I.E.E.* 1910, vol. 48, p. 620.

* *World Power*, 1924, vol. 1, p. 91.

† *Electrician*, 1892, vol. 29, p. 87.

‡ *Ibid.*, 1905, vol. 56, p. 468.

the breadth and thickness respectively, and K has the following values:—

Length ..	2 in.	2·5 in.	3 in.	3·5 in.	4 in.
K ..	30 000	26 500	24 000	21 700	20 000

According to Preece's formula a No. 18 S.W.G. aluminium wire in air would have a minimum fusing current of 50 amperes, and according to the above formula an aluminium plate fuse having the same sectional area as the 18 S.W.G. wire (i.e. $b = 0 \cdot 15$ in. and $t = 0 \cdot 0125$ in.), would have a minimum fusing current of 63·5 amps.

APPENDIX 2.

Standardization.

In the interests of users, efforts have been made both here and abroad to standardize fusible cut-outs of various types, and Table 3 shows very broadly a comparison between some of the most important clauses in the regulations.

Table 3.

Authority	Fusing factor limits	Short-circuit current to be broken safely	Permissible temperature-rise	Other features
A	1·4 to 1·5	10 000 amps.	70 deg. C.*	To be non-interchangeable
B	1·3 to 2·0	—	—	—
C	—	1 000 amps.	—	To be non-interchangeable
D	1·5 to 1·2	—	—	—
E	1·3	500 amps.	—	To be non-interchangeable and fitted with indicator
F	2	33 times normal † 330 times normal ‡	30 deg. C.	—
G	2	Up to 6 500 amps.	30 deg. C.	—
H	2	Up to 6 500 amps.	30 deg. C.	—

A = National Electric Code of America.
B = Union des Syndicats de l'Electricité.
C = Verband Deutscher Elektrotechniker.
D = Règles de normalization pour le gros appareillage électrique arrêtées par la Chambre Syndicale des Ingénieurs.
E = Bulletin de l'Association Suisse des Electriciens.
F = I.E.E. Regulations for the Electrical Equipment of Ships (First Edition).
G = I.E.E. Wiring Rules (Eighth Edition).
H = British Standard Specification (No. 88) for Low-pressure Cut-outs.

* At 110 per cent normal current. † Ordinary duty. ‡ Heavy duty

THE DIRECTION-FINDING EQUIPMENT AT NITON AND CULLERCOATS.*

By J. H. Reyner, B.Sc., Student.

(Abstract *of Paper read before the* London Students' Section, *28th November,* 1924.)

Summary.

The Niton and Cullercoats stations are the first to be equipped by the G.P.O. for a regular direction-finding service. The apparatus, which is of the well-known Bellini-Tosi pattern, is briefly described and the methods employed in taking a bearing are discussed.

The satisfactory installation of the apparatus is followed by a calibration in co-operation with a ship. Experience shows that this is absolutely necessary, owing to errors introduced by objects in the vicinity of the station. The method is described in detail, and the error curves obtained are analysed with reference to the local conditions.

The influence of neighbouring bodies on the error curve is investigated, and it is shown that the deviations obtained may be expected to remain constant. Experience indicates that this is true, so that a station which at first sight appears to be poorly situated may be capable of providing a reliable service if suitable precautions are observed.

Description of the Apparatus.

The apparatus employed for direction-finding consists essentially of a suitably erected frame aerial on which the particular station is received. The frame is rotated until the signal strength is zero or a minimum, at which point the frame is at right angles to the direction of propagation of the wave, i.e. the bearing of the station.

The equipment employed at the Niton and Cullercoats stations is of the Bellini-Tosi pattern, in which the simple rotatable loop is replaced by a system of two large loops erected accurately at right angles, the rotation being effected electrically.

The leads from the loops are connected to a radio-goniometer which comprises two field coils mutually at right angles, with a rotating search coil in the centre. An electric wave passing the aerial system induces currents in the loops, and these currents, passing round the appropriate field coils, set up magnetic fields in the goniometer. The resultant of these two fields (at right angles) can be shown to be fixed in direction and to have the same orientation relative to the field coils as the electric wave has to the external loops.

As the search coil is rotated, therefore, the signal strength will vary from a maximum to zero, the position of the zero depending on the direction from which the signal is coming, so that the final effect is the same as that of rotating one of the large loops.

Tuner and receiver.—For reasons of simplicity of operation and accuracy of results, it is now customary to employ a large search coil tightly coupled to the field coils, the loops themselves being untuned. The search coil circuit is tuned and loosely coupled to a "jigger" circuit, which is also tuned, the voltage across the condenser being applied to a seven-valve high-frequency amplifier, of which only three or four

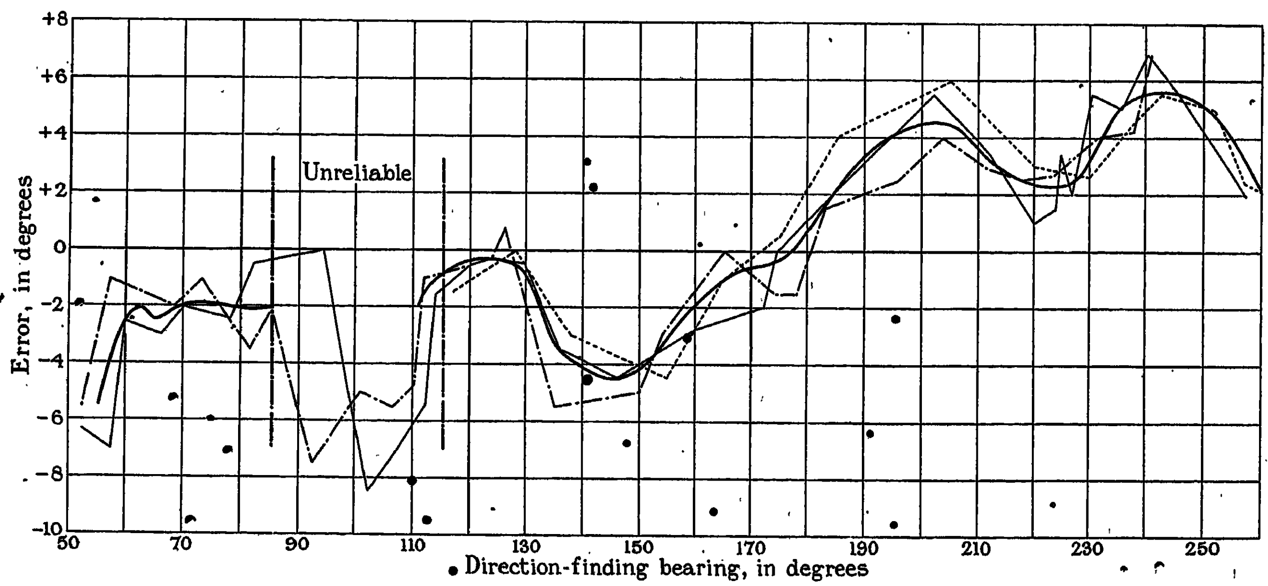

Fig. 1.—Error curve at Niton.

* A Students' Premium was awarded by the Council for this paper, and it is the practice of the Council in such cases to publish the paper, in full or in abstract, in the *Journal*.

valves are normally required. There are also two optional stages of note magnification.

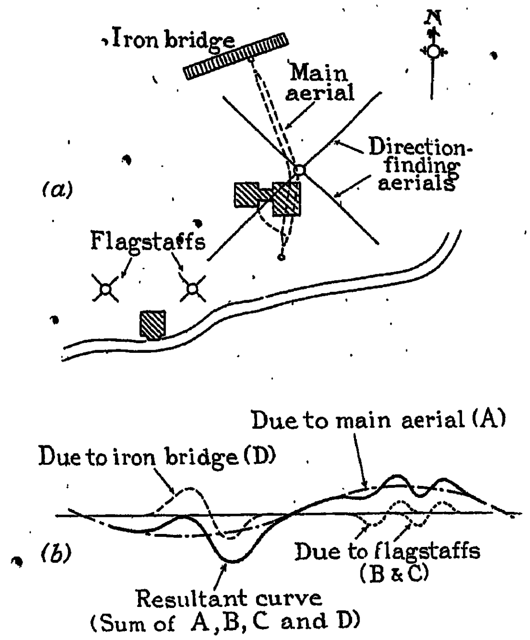

FIG. 2.

The middle points of the field coils of the goniometer are connected to earth, as otherwise electromotive forces are introduced due to the action of the frames as aerials. Such E.M.F.'s are independent of the direction of the signal and so lead to false bearings. The earthing is effected through a three-position switch. In the first position, the frames as a whole act as an aerial. In the second, the aerial effect is cut out and the direction of the signal may be obtained with the goniometer. There are, however, two zeros 180° apart. In the third position, therefore, the frame and aerial effects are combined to give a minimum in direction which indicates the true bearing.

To avoid "direct" pick-up, all the various units are screened. For further details of this system reference may be made to a work by R. Keen.*

METHOD OF TAKING A BEARING.

To take a bearing the approximate zeros are noted, and the "sense" of the bearing is determined. The actual zero points are then obtained by taking small swings on either side of the minimum, noting the readings at which the signals are of equal strength. The mean of the two readings gives the actual zero. This method is adopted because the zero itself is indeterminate over 2 or 3 degrees.

In addition to the true bearing, the reciprocal is also observed, and 180° added or subtracted as required. These two bearings, which form a pair, should agree, and as many pairs as possible are taken in the time available (usually one minute). If the bearings in a pair do not agree it indicates that some aerial effect is present, so that the bearing obtained is not correct. A dis-

* R. KEEN: "Radio Direction and Position Finding."

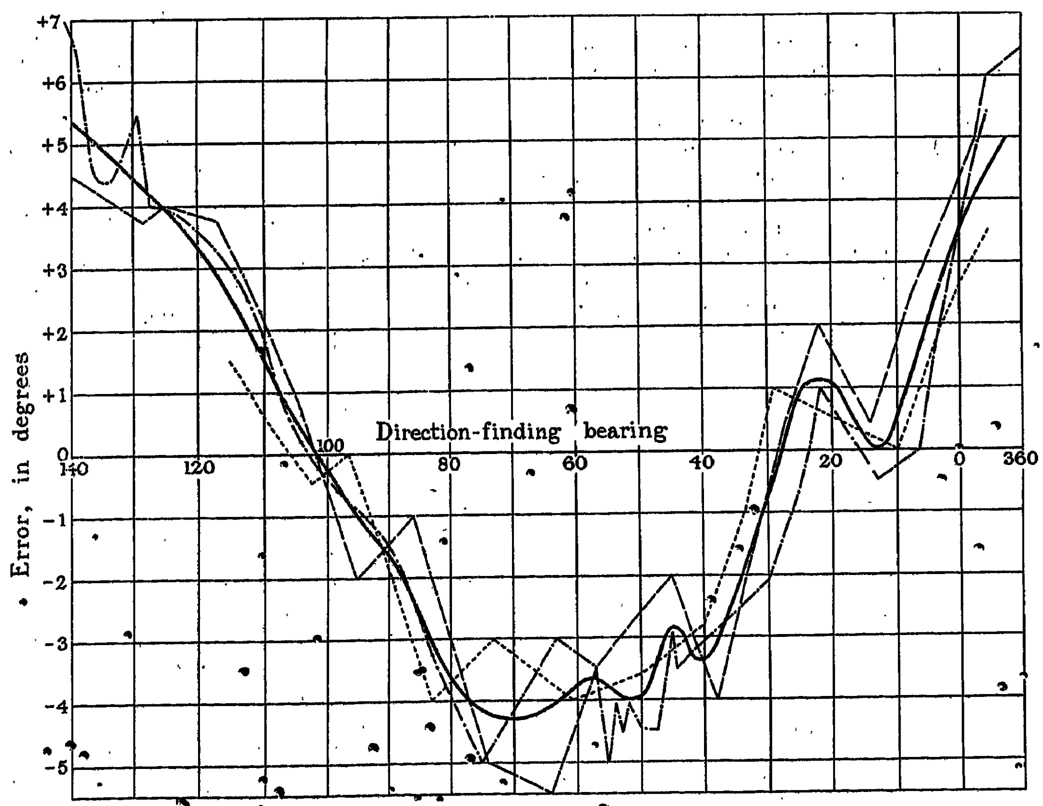

FIG. 3.—Error curve at Cullercoats.

crepancy of 2° is permitted ; if the difference is greater, the bearing is repeated. The main aerial of the station is disconnected during the taking of a bearing, as otherwise all bearings are found to be in the plane of the aerial.

Calibration.

The apparatus, when installed, must be calibrated. The goniometer is adjusted approximately by taking bearings on known fixed stations, but it is necessary to employ a ship to steam over the effective arc, sending signals every few degrees.

The actual bearing at these points is determined by visual observation with a theodolite, and the error can thus be plotted. The curves usually contain unexpected irregularities, indicating that a calibration of this sort is essential.

Analysis of Results.

The Niton error curve is shown in Fig. 1. Three runs were made over the arc, and these are in reasonable agreement (allowing for operation errors). A mean curve is drawn through the three.

The sector 85° to 115° is classed as unreliable, the deviations from the mean curve being too large. The curve itself is also too steep ; e.g. at 111° an operation error of ½° would make a difference of 2° in the true bearing. The coast line at Niton makes angles of 85° and 310°, so that this is probably due to coast effect, it being well known that bearings within 20° of the coast line are unreliable. The sector 55° to 85° is again reliable, but there is a permanent error due to coast refraction.

Referring next to the irregularities on the curve, these can be shown to be due to objects in the vicinity. Fig. 2 (*a*) shows the surroundings of the Niton station, there being several masses of metal quite close to the aerial system. These objects have currents induced in them, which set up secondary radiations combining with the main radiation and tending to distort all the bearings in that region into the plane of the metallic mass. Thus the main aerial, even though disconnected, tends to distort all bearings into its own plane (here 180°), giving rise to an error curve as at A in Fig. 2 (*b*). This curve is the principal error and is termed a " quadrantal " error, being alternately positive and negative in the four quadrants.

Next, the flagstaffs at 215° and 235° distort the bearings into these planes, e.g. 213° will appear slightly more, and 217° slightly less. This effect is only apparent on bearings from the south-west, and gives rise to two small curves B and C in Fig. 2 (*b*). Finally the iron bridge, though behind the station, will distort bearings from the south-east into the plane 320° (140°), as shown in curve D. Since the bridge is behind the station, curve D is reversed compared with B and C. The sum of all these effects will be seen to resemble the actual curve very closely over the sector 115° to 260°.

The error curve for Cullercoats is shown in Fig. 3. It will be seen to be composed of a quadrantal error, due to the main aerial as before, with three deviations superposed. The curve is thus of the same form as at Niton, and could be built up in the same way.

If this explanation of the deviations is correct, the error curves may be expected to remain constant; and experience indicates that this is the case, so that these calibrations may be considered to be reliable. As an additional precaution, however, they are periodically re-checked.

Conclusions.

The following conclusions may be drawn :—

(1) It is essential to calibrate a new direction-finding station over the whole of the effective arc, which extends up to 20° from the coast line. Check-bearings on fixed stations are only useful for preliminary adjustments.

(2) The error curves usually take the form of a quadrantal error due to the main aerial of the station, with minor deviations occasioned by any metallic masses in the vicinity.

(3) The deviations appear to be caused by re-radiation from the various objects, such re-radiation being in a direction tending to distort the bearings into the plane of the interfering objects.

In conclusion, the author wishes to express his thanks to the Post Office authorities for permission to publish the information given in the paper, and to those of his colleagues who have assisted in the analysis thereof.

ECONOMICS AND INDUSTRIAL ELECTRIFICATION.*

By A. TUSTIN, M.Sc., Student.

(*Paper read before the* NORTH-WESTERN STUDENTS' SECTION, 11*th November*, 1924.)

SUMMARY.

This paper attempts to define exactly at what we should aim in a policy of power supply, and discusses how we may decide which among the many alternatives will best achieve this aim.

In this connection it is found necessary to discuss :—

(1) The degree of dependence of our foreign trade upon cheap power.

(2) The implications of the ordinary methods of comparing the economy of various schemes.

Lines of investigation are suggested by which the best policy may be selected, and the methods of charging for power which it would be desirable to adopt are discussed.

POWER SUPPLY.

Comparative estimates for power proposals.—It is desirable before discussing alternatives of policy to state very clearly at what result the policy aims, so that a standard will be available by which the alternatives may be compared.

This is neglected by writers on power supply, who usually stress beyond proportion some particular alleged benefit expected to follow the application of their proposals, for example the conservation of our coal resources, or the making of nitrates within the Empire. More commonly they are content to prove that their proposals would enable power to be generated at a lower cost per unit than at present, and they assume that every one will agree that this is a desirable thing.

Power costs and foreign trade.—The universal argument advanced in support of cheap power is that it would enable us to compete with more success in the markets of the world. It is worth while to examine this argument, and to state clearly that—

(1) Whatever our costs of production, we shall always be only just able to compete abroad.

(2) The increase in the standard of living which a power scheme would make possible would be extremely small.

To establish these most important points it is necessary to outline certain principles of foreign trade.

The error which it is important to avoid is the assumption that because a country, say Russia, can manufacture, say, iron goods more cheaply than England, then it will be impossible for England to supply the world's markets in the face of Russian competition. This is not necessarily true. Leaving out all the complication of other countries and products, let us suppose that Russia also produces wheat, and produces it not only cheaper than the same quantity could be grown in England, but also proportionately cheaper that Russian iron (by "cheaper" being meant "at less expenditure of labour and capital," not cheaper in the monetary sense, since, owing to goods in Russia being priced in roubles and goods in England in sterling, which of the two is the cheaper in money depends entirely upon the rate of exchange).

Suppose now, as at first seems probable, English merchants purchased both iron and wheat in Russia. The result would be that English money would accumulate in Russia, where it is useless unless it is used to purchase goods in England. The level of value of English money in Russia would therefore fall. As it fell it would first pass the limit where iron ceases to be cheaper to buy in Russia than in England. A little farther on it would become profitable to buy iron in England, and sell it to Russia. The conditions for a steady mutual trade would now exist, and it will be seen that—

(*a*) England would make iron goods and exchange them for Russian wheat.

(*b*) The maximum real economy is secured in this way.

(*c*) There exists some ratio of monetary exchange at which merchants on both sides could make a profit.

If the currency were gold instead of notes the above argument would still hold good, only, instead of the ratio of exchange altering, the price levels of the two countries would move oppositely under the influence of gold payments and exactly the same result would be obtained.

The above fictitious example is not intended to be more than a sort of mental diagram, which may convey this important idea to those to whom it is not already familiar. It is an example of a general principle which applies throughout the most elaborate processes of exchange.

This country is destined to an industrial development growing more dense rather than less dense, not only because it is fairly well suited to manufacturing, but also, and more significantly, because it is relatively unsuited for anything else. We shall be able to compete abroad not because we have cheap power, which is a small matter, but because we can neither decrease the population of these islands nor transfer our huge fixed capital abroad. The logic of events will reduce our standard of living until we just do compete, and the irrational optimism of human nature will try to see to it that we just do not. A fluctuating equilibrium will be attained, and it must always seem, as it seems to-day, that only a little extra is needed to turn the scale, and

* A Students' Premium was awarded by the Council for this paper, and it is the practice of the Council in such cases to publish the paper, in full or in abstract, in the *Journal*.

that 5 per cent off this or that would establish our markets on a firm basis. It is like watching the lap of the waves and forgetting the tides.

So far as power is concerned the author contends that, if all our coal were destroyed to-morrow, we should import coal and perhaps electrical energy and develop very expensive water and tidal power, and apart from temporary disorganization we should carry on in the long run with very little change in our standard of living. It follows that cheap power has practically no effect on our ability to compete in the world's markets, and also that we need give no thought to the possible exhaustion of our 500 years' supply of coal.

The change in our standard of living which a scheme of electrification would make possible would be equal to the proportion of the cost of production of our whole national output which it saved. This would be extremely small. To get the subject into focus let us consider a few approximate figures. The present cost of production of the whole annual products of the United Kingdom is greater than £3 000 000 000. The annual cost of the coal used for power production taken at £1 per ton is about £80 000 000, or 2·6 per cent of the costs of production for the country. The cost of the coal used in generating electricity in power stations is about £7 000 000, or 0·23 per cent of the costs of production.

Figures for the individual industries entirely confirm these averages. The largest industry is agriculture, where the cost of power is negligible. For coal mining, where the waste of coal in steam-raising is notorious, and where the fuel actually burned is often of low grade, only 17 million tons are burned in producing 270 million tons. The fuel cost is therefore necessarily less than 17/270, i.e. 6·3 per cent of the cost of production.

In the textile industry the following are the approximate figures, which are based upon official averages for the trade :—

Mule spinning.—In a typical mill the cost of coal is 4·9 per cent of the cost of production, excluding the cost of raw material and commercial charges.

Ring spinning.—The percentage is slightly less.

For the whole textile industry the coal used per head is about 8 tons per employee per annum.

For a typical electrical engineering factory about 6 tons of coal per employee in the works (excluding offices) are used per annum. This includes coal for all purposes, heating, lighting, cooking, and forge fires. This represents about 4·5 per cent of the cost of production, excluding raw material.

Electrification could save only on fuel costs, and part of the saving would be offset by the capital outlay, and it is therefore clear that a saving of a small part of 5 per cent only is all that can be hoped for at the best from power reform. Those prophets who base their hopes of prosperous times upon improved power supply will therefore be disappointed. All saving, however, is good, and though the proportion is small the total is large.

Power supply policy.—Setting aside therefore baseless hopes and ill-considered standards, we may ask the question "What are we really aiming at in a scheme of power supply, and how can the merits of the many alternatives be compared?" Electrification is, after all, only a method of indirect production, and must only be employed when it is the method of production most fruitful of value. It is hard to see why there is a cry for cheaper power, and not for cheaper machinery or lower railway rates. Just as no one would suggest huge and costly developments of machinery manufacture in order to produce cheaper machinery, so any artificial treatment of power production must avoid diverting resources to development which may not be in the general interests of the nation.

We must admit that the standard of living of a people cannot be greater than that of the rest of the world unless they have greater resources, or handle their limited resources with greater skill. The author feels that this people can only avoid a very unprosperous half-century by the absolute elimination of waste, not only of power but of every value, and by the deliberate adoption of a policy of insisting with the utmost realism upon those forms of effort and development which will give the greatest return of real human value for effort involved. This is what we mean by real economy, and our aim in power policy is to secure the maximum economy in this sense, that it should contribute to the maximum to the real human value which our national effort can secure.

No one is likely to dispute that in course of time our power supply system must be developed on the general lines of larger stations, defined districts, and interconnection of supply. At the same time, there are widely different possibilities with regard to the rate of development and the ultimate intensity, with a view to which the lines of present development are to be decided. Some more exact definition of our requirements is therefore needed. The cheapening of the cost of power per unit which is advocated would usually apply only to an increased production and consumption of electrical power. Visualizing a more and more intensive electrification, it is clear that the cost of energy would progressively decrease, though, after a certain stage, only slowly.

The amount of electrical power which industry will use is a function of its price. The lower the price the more will be used, but not to an indefinitely large amount. Clearly, then, if electrification is to be extended the basic question is: "Which falls the more quickly as electrification is increased, the cost of generation or the price at which industry will take the increased quantity?" At some point there is a limit, which corresponds to the ordinary commercial limit, beyond which electrification does not "pay." This limit may be very different from that which would be thought of if one set out merely to produce a scheme which would give cheap power. There must be a proper comparison of cost and return so that the limit beyond which electrical development does not "pay" may be found. An important question about this limit is whether, when found, by analysis or experiment, it corresponds to the true best national policy, or whether public policy must with truer vision transcend this "wrangling of the market place" and deliberately use national resources to secure national advantages which are left out of the commercial balance sheets. This question, of course, verges on politics, but political argument will not answer

it. It is a technical problem and depends for its answer upon a consideration of how costs are arrived at, just what realities they include and what they omit.

For this reason, and to attempt to clear up certain difficulties in the use of comparative estimates in every-day practice, in the next section an analysis is given of the way in which costs and values are compared.

The Correct Measurement of Comparative Economy.

It has been agreed that real economy is the return in human value for effort involved. Since in ultimate analysis both value and effort are matters of individual feeling and not of reason, true economy can never be logically defined except with explicit reference to the will of the people. Economy, and even comparative economy, are not constant—they are in their nature elusive and indefinable things, matters of taste. The ordinary commercial standard of economy, that of profit, the difference between cost and value, has the great merit that it does reflect in some way this popular valuation, which is simply demand and supply. Because of this the author thinks that cost and commercial value will always be important and useful measures of economy, but it will be necessary to find out just what the implications of this standard are, and how far the judgments of value which its adoption implies are really those which would be consciously endorsed by the community. That commercial estimates omit many things will be obvious, but as a small concrete example we might take air pollution. Smoke costs London annually £17 000 000, and England £200 000 000, and these sums enter into no comparative estimate and appear on no balance sheet. In public enterprises, such as power supply must necessarily be, such considerations are not without real significance.

Commercial comparative estimates.—It will therefore be worth while to examine the way in which comparative estimates are usually made. The simplest type of economic problem is one which concerns material alone, like those in mathematical textbooks about making the largest possible tin can out of a sheet of tin. So long as we are dealing with material of one sort, say comparing one set of machinery with another, or comparing the economy of a large quantity of cheap coal with a less quantity of expensive coal, there is no doubt that we can safely compare their costs. Actually, however, we have also to find some basis to compare expenses of different kinds. For example, the whole question of power development concerns a proposal to expend a great amount of work upon power stations in order to save continual work upon coal mining.

We are really making two comparisons here. In the first place we are comparing work done on power stations with work done in coal mining, and we compare the money costs of both. Do we really believe that the relative desirability of diverting people towards the labour of mining rather than the labour of engineering is exactly measured by the relative lowness of miners' wages?

In the second place we are comparing work done now with continual work done in the future. This is very simply done in current discussions by the adoption of the money costs of both and the reduction of capital costs to an annual cost by the use of the rate of interest. Apart from the fact that the real rate of interest referred to standard securities fluctuates widely and can seldom be measured by 5 per cent, can we really be satisfied that this method gives a true standard of comparison?

Furthermore, development of capital can only be made at the expense of current consumption. During the active phases of the industrial revolution the people of this country had not enough to eat, whilst hundreds of millions of pounds were being sunk in building factories and railways; but no doubt the desirability of so diverting current consumption to capitalization was measured, if not by 5 per cent then by some equally haphazard figure. Equally there are periods when our productive machinery and labour are half idle and it is still thought public policy to calculate on this 5 per cent before setting them to public work. It would therefore seem that (1) for public enterprises considerations of public policy should not take too much account of this 5 per cent, and that (2) private enterprises might pay some attention to the actual rate of real interest which will probably hold during the life of the plant, including all changes in price-levels. If the private enterpriser thinks that this and similar points are not sound finance, one can only add that by neglecting them he forgoes enterprises which would have yielded him more profit than he otherwise gets, and he accepts obligations which yield him less profit, neither of which is part of the function of an efficient private enterprise.

Kelvin's Law.

Among the problems which involve the rate of interest the best known are those of the type of Kelvin's law for the economical size of a conductor. It is well known because it admits of a simple mathematical solution, the answer being that the size is correct when the annual cost of the conductor (as measured by the rate of interest multiplied by the first cost) is equal to the annual cost of the energy lost in it. It is rare that the conditions are so simple that a mathematical solution can be found to problems in engineering economics. Even Kelvin's law is not quite true as it assumes a straight-line relationship between the cost and the copper section; and it neglects voltage-drop and heating limits. Such problems are invariably solved by comparative estimates with a series of variations, and the result is, of course, that we choose what the right answer would have been if we had taken every condition into account and had been able to solve the resulting equations. The value of Kelvin's law is chiefly mental. To have once become really aware of this type of argument greatly helps one's understanding. By acquiring a sort of mental framework of such ideal problems we are able to think more clearly and with greater ease about actual problems. In practical application the author would rather invert the emphasis on Kelvin's law and say that it does not show the importance of selecting the cable of economical section, but rather its unimportance; since it shows that for even a large variation from the most economical size the increase in cost tends to be counterbalanced by the saving of

energy, i.e. the curve of total annual cost is very flat-bottomed.

DEPRECIATION.

Since everything tends to deteriorate in the course of time, it is necessary in comparing economy to allow for depreciation. Money may always be invested in standard securities, where it will earn a certain rate of interest. If the alternative presents itself of investing the sum in plant, it is clearly wrong to say that the money should be invested in plant if it will earn as much as or more than the income which it would earn if invested in securities, because after, say, 25 years the plant will be worn out but the securities will still have their full value. To find when the two investments become of equal value is simply a matter of arithmetic. It is simply required to find what annual return lasting 25 years only is an adequate return for the complete abandonment of a sum of money for ever. This neglects any value of the "going concern" as giving a value to the opportunity of replacement. Exactly the same answer of course would be obtained if the problem were put the other way round, i.e. "It is required to find the present value of this particular income which lasts for 25 years." In fact the latter is a better way to put it, because it allows for the fact that the income may be spread unevenly over the 25 years. It would in this case still be possible to calculate its equivalent present value, and to say that this value is equal to the maximum capital expense which such a prospect of income would justify.

The necessary "ratio of interest and depreciation" for various "lives" at various rates of interest are easily calculated, but as they are given in tables for the present value of terminable annuities this saves the trouble of calculating them. It is worth while calling attention to the fact that the choice of the right depreciation rate is exactly of the same degree of importance in comparative estimates as the right estimation of the capital cost. To estimate capital outlay minutely and then be uncertain as to whether to use 8 per cent or 12 per cent as a correct interest factor is illogical, because 12 per cent taken instead of 8 per cent is exactly equivalent to and indistinguishable from an increase of the capital cost by 50 per cent. The following table will give an idea of how the right figure varies.

Years of life	Percentage rate	Interest and depreciation, per cent
10	5	12·9
15	4	9·0
	5	9·63
	6	10·3
	7	11·1
20	4	7·36
	5	8·02
	6	8·72
	7	9·45
30	4	5·78
	7	8·06

Depreciation in accountancy.—The endless argument about the correct charging of depreciation in cost accounts has arisen from a failure to distinguish clearly the different purposes which a depreciation charge is expected to meet. Since these several purposes can only be correctly attained by quite different methods of charging, the confusion is understandable.

Some of the requirements are :—

(1) To maintain the balance sheet in a condition which shows the true state of the firm, or, as required, some other state.
(2) To provide a fund for the replacement of the plant at the end of its life.
(3) To give a guide to values in the case of sale, scrapping or replacement.
(4) To arrive at true factory costs for selling.

Further to these requirements, bookkeepers have added muddled ideas borrowed from the depreciation for comparison of economy described above, and the whole argument has been complicated by the curious popular fallacy that the value of an article depends upon how much was paid for it and how much has been written off since. This discussion will not now be carried further, but it is inserted as a warning against attention being paid to the bookkeepers' ideas of depreciation.

Obsolescence.—The power of a piece of apparatus to earn income, i.e. its value, may disappear, for other than physical reasons. It obviously does not matter how it disappears ; the depreciation charge must correspond to the probable duration of the earning power, and, if it does so, everything is allowed for. An obsolescence charge does not differ in principle from a depreciation charge. Obsolescence is all depreciation which does not arise from the plant itself, but from outside causes. Such a charge is quite valid and necessary in comparing economy. The fact that it cannot be determined in advance for certain when a plant may lose its earning power is no reason for neglecting the possibility. The estimate should be based on the estimated probabilities.

An example of obsolescence is seen in a comparison of the use of gas engines as opposed to oil engines on oil fields, to utilize the natural gas which is often available. The supply of such gas very often falls off after some time, and on that account Diesel or steam engines are often installed from the beginning. There is no reason, however, why the judgment should not be helped by comparative estimates based on the probable duration of the gas supply, and this factor would be accurately taken care of by the appropriate higher depreciation rate corresponding to the short probable useful life of the gas engines.

An interesting cause of "obsolescence" is technical progress. Commercially it is obvious that the chance of a new competitive process springing up is a chance that any plant may lose its value. It is a striking paradox that a discovery that enriches mankind as a whole automatically destroys the value of the property of certain persons.

In connection with power supply, due consideration should be given to the quite considerable probability

that technical advances will be made during the next decade or two which will render our present generating practice obsolete; one thinks in this connection of super pressures, gas turbines, low-temperature carbonization, cheaper transmission, or even new sources of energy. Perhaps electricity will become a by-product, and in this case its price may fall to any low value. Are we certain that any line of development we adopt to-day will still be the right line of development in 20 years' time? Technical progress was never so rapid as it is to-day. All these possibilities are properly taken into account by allowing a rate of depreciation which includes for "probable obsolescence" and loads the balance against all proposals to sink large values in premature development.

The Accountancy of Real Values.

The foregoing discussion of the usual methods of making commercial comparisons has shown that they can only go part of the way towards making the real economy as large as possible, because there are very many facts which are left out of account altogether. In the public supply of electricity, policy cannot be determined without an implicit decision upon this preliminary question of how far the ordinary commercial standards of profitableness must bind public policy. The question now at issue is whether the Government must of necessity either not touch financial matters or, if it does, be bound by the same necessity of showing a monetary return for all its monetary expenses and investments as binds a private firm. This suggests possible functions of the Government quite distinct from those functions, which all will admit, of co-ordination, certain legislative control, the prevention of monopoly exploitation, and constructive guidance.

To be able to answer such questions is a great need of our times, and the author feels sure that the appropriate analysis and an accountancy of real values will be built up in the future. He suggests that, failing this more complete analysis, rigorous estimates on the lines of commercial estimates must be made and must bind decisions, but that it is permissible for, and indeed a function of, the Government to include in these estimates a monetary equivalent of national values, or of national disadvantages, which would not enter into the determination of policy if left to private enterprise. Hence Government enterprises need not "pay" on a cash basis, but they must pay on a basis of the accountancy of national values. The chief value of the commercial system is that it provides automatic adjustments and checks, but there is no reason why its advantages should not be retained in national enterprise by proper accountancy. There is no real reason why charges should be equal to the actual cash paid. The function of such accountancy is that of a scoring board in a game. It is important that the real "values" be marked up independently of what it may be convenient or necessary to pay in cash. For example, unpleasant trades might be discouraged by a higher "wage" for purposes of this scoring-board accountancy, without necessitating the actual payment of higher wages in that trade. This is of course impossible except in communal enterprises.

Apart from these deliberate and defined departures from commercial economy, it seems to the author that the ordinary commercial limits must be rigorously adhered to, because to cut adrift from them leaves us without any anchorage at all, free to follow some ideal wherever it may lead, which is only all right so long as we leave nothing out of account, and in the world of ideas it is easy to leave out some factor which would have been unpleasantly obvious in a balance sheet and which the "wrangling of the market place" would not have neglected.

The selling of energy.—The author has shown that producers of energy under any system must sell at such prices as will show no loss. A proposed system must justify itself by being able to build up its load soon enough to give a return on the capital invested. The reduction of the income expected during the life of the plant to an equivalent present value would be carried out on the lines already indicated. This income would probably be distributed very unevenly throughout the life of the plant. The return for the first several years of the inauguration of a scheme of power reorganization might economically be negative in some cases, that is, it might be economical to sell energy below net cost. This does not mean that it should be sold only below gross cost, which is, of course, a commonly accepted principle, for if a new supply system would be otherwise underloaded it obviously pays to accept load at a price which only includes the fuel and labour charges dependent upon this extra load, and not the interest, rent, taxes, etc., which have to be paid in any case, provided that the load otherwise could not be obtained. This, however, is selling at real cost so far as these extra units go, not below cost.

In an exactly similar way it might pay in some cases to sell some power below the apparent net extra cost of producing these units. This is because as we consider a series of schemes of progressively more intensive electrification the efficiency will in every way be progressively higher, and with each imaginary addition to the output the cost of production of *all* the units generated may be imagined to fall slightly. Hence the additional cost of generating additional units is really less than the cost taken at the average for the station, i.e. we are concerned with marginal cost, which is in this case below the average cost. It is debatable whether a power supply undertaking could economically make still further cuts in price over a period of years for the purpose of building up load. This question is of some importance in view of the developed nature of the industries of this country, which will make all those processes of conversion based upon normal power prices extremely slow. An artificial "dumping" of energy in a defined area to *new* customers for a limited period sufficient to encourage immediate conversion to electric drive in a large number of factories would tend to raise the load at once, and bring into line those conversions which otherwise would have been scattered over a long period. If the employment of this device would make possible the installation of a power system which would otherwise have been impossible, the author sees no reason in economics, law, equity or public policy, why it should not be deliberately employed. Without

such a device, in cases where plant is replaced piecemeal as elements wear out, it seems possible that a technically out-of-date plant might have its existence indefinitely prolonged without a complete reorganization ever appearing profitable.

Methods of charging.—In general there are available two quite different systems upon which the charges of a monopoly undertaking may be based. The first is that of cost plus profit, "cost" of course taking into account load and power factors and all the circumstances of supply. The other is called by two alternative titles, according as the speaker is a supplier or a consumer. The supplier calls it "Selling at the value of the service," the consumer "Charging the maximum monopoly revenue." Economists sometimes call it "Charging what the traffic will bear." The author has assumed in the above discussion that this is the principle which will and should be adopted in selling electrical energy, and the reasons for this will now be given.

Selling at monopoly prices.—That the public interest may best be served by a public supplier charging as much as he can get is only true if his receipts are not spent upon private diversion, but used to enable a corresponding amount of product, which would otherwise not be produced, to be sold below apparent cost. This argument is therefore no defence of private monopoly without restriction.

An attempt will be made to justify the statement that on the average a public supplier should sell at cost, but that for the separate parts of his production he should sell for the maximum he can get. In all cases of joint supply, of which electricity supply is an example, there is really no such thing as a cost for each particular part of the output. There is a cost of raising sheep, for example, but no separate costs of producing wool and mutton respectively. If the demand for mutton were low enough (as in Australia before refrigeration) one might have to pay a man to bury it, yet it would still be produced, and if a penny a pound could be obtained for it it would be sold "profitably" at that price. No one would contend that in a theatre each seat in the stalls really costs, to install and maintain, six times as much as a seat in the gallery. On the average all the seats in a theatre together just about pay the expenses of running. If all the seats were charged at this average price the theatre would be less used, as those who use the cheap seats would not be likely to pay much extra for the chance of getting a front seat. The running of that theatre would therefore be impossible, and all those who previously got an entertainment worth more to them than the amount they paid (otherwise they would not have come) must now be without that opportunity. In this case, then, charging what the service will bear seems socially justifiable. Half a power system is economically very like half a theatre. It is worth while putting in a gallery and charging less than apparent cost. It is right to charge stall-holders the maximum they can be made to pay in order to enable this to be done; and it would be manifestly unjust to charge as much for bad seats as for good, because they cost the same. The argument usually advanced against this position is one which mistakes its real intention. For instance, it would be proposed to charge a very high rate for lighting in a select suburb, as these consumers would rather pay a high rate than go without the amenities of electric light. It is then argued that the high prices for lighting restrict its use below the natural economic level. This is obviously the reverse of the truth, for the whole aim of the rate is to be low enough (even if only just low enough) to secure that particular market, and the extra income thus obtained may be used to extend the sale of electric light below apparent cost in suburbs which are not select. The adoption of this policy might multiply the use of electric light to an indefinitely great extent if a large field were just upon the margin of use. The same principle of differential charging is used to fix railway charges, and though the strange apparent anomalies of railway rates are criticized by those who have most to pay, there is no doubt that they have made possible the development of our railway system.

Superficially a system of charging what each consumer can be made to pay seems unjust. For example, a mill may have been electrified for some time. If the owners then find that on the occasion of power system extensions a neighbouring mill, to persuade it to make a change-over, is offered a very much lower tariff, they may ask for a reduction also. The fact is, however, that the real cost of electricity supplied to the second mill actually is very low as it is an extension of the existing system, and only on the basis of charging a low price and on no other system can the advantages of this real economy be made available to the nation.

It is not necessary that the absolute maximum monopoly revenue should be sought from consumers who could ill afford to go without electricity, nor is it suggested that electricity should ever be supplied below the bare cost of generation for that particular demand, the special circumstances of a temporary low price already mentioned being allowed for. The real theoretical position seems to be that sales should be carried to the limit that is fixed by the marginal cost of production, and not the average cost of production, and by the marginal value of supply to the consumers, not the average value of supply. For consumers other than those at the margin the price should be low enough to induce and maintain the market, and the average price should be high enough to cover total inclusive costs. In short, while this paper suggests that though electrical development must justify itself on a basis of earning power, it is at the same time allowed the benefit of driving a bargain, in the knowledge that an industry will not pay for electricity more than the value of the benefit which that industry obtains from it. This higher value of electricity in certain applications must be properly accounted on the "scoring board" which the system of charging really is, and this accounting will, so far as it goes, enable the true maximum of real value to be obtained.

The adoption of such principles for charging, together with the inclusion in comparative estimates of those factors which market prices neglect, appears to be the basis needed at the present time in order to secure some agreement among the many advocates of power reform.

INSTITUTION NOTES.

International Conference on E.H.T. Lines.

The Secretary has been requested to draw attention to the following Note which appeared in No. 346 (October 1925) of the *Journal* :—

It is proposed, subject to there being a sufficient demand, to publish an English edition (in two volumes of about 1 100 pages each) of the papers read at the International Conference on E.H.T. Lines held in Paris from the 16th to the 25th June, 1925. The volumes will also contain a report of the discussions.

If the demand reaches 400 copies, the price will be £4 for the two volumes, but in the event of 800 copies being subscribed for, the price will be £2 10s.

In order that an early decision may be arrived at as to whether to publish an English edition, those wishing to subscribe for copies are requested to inform without delay.

Monsieur Tribot Laspière,
Union des Syndicats de l'Électricité,
25, Boulevard Malesherbes,
Paris,

of the number of copies they will require.

A French edition of the papers and discussions will also be published, provided not less than 1 000 sets are subscribed for. The price will be 200 francs per set, but after the 1st November, 1925, the price will be increased to 250 francs. Orders for the French edition should also be sent to M. Tribot Laspière at the address given above.

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 September–25 October, 1925 :—

	£	s.	d.
Anonymous		2	6
Felix-Smith, L. E. (Auckland, N.Z.) ..		5	0
Lee, T. F. (London)		10	0
Longman, R. M. (Leeds)		10	0
Maquay, G. A. (Chicago)	1	0	0
Pickersgill, A. (Cleckheaton)		5	0
Round, H. J. (Chelmsford)	5	0	0
Shire, B. (Birmingham)		7	6*
Walter, C. M. (Birmingham)	1	1	0
Western Centre	22	2	8

* Annual Subscription.

Accessions to the Lending Library.

Aitken, W. An outline of automatic telephony. sm. 8vo. 143 pp. *London*, 1925

Andrews, E. S. The strength of materials. 2nd ed. 8vo. 618 pp. *London*, 1925

Annett, F. A., and Roe, A. C. Connecting and testing direct-current machines. 8vo. 247 pp. *New York*, 1925

Baldwin, F. G. C. The history of the telephone in the United Kingdom, with a foreword by F. Gill, O.B.E. 8vo. 754 pp. *London*, 1925

Braymer, D. H., and Roe, A. C. Rewinding small motors . . . fractional horsepower d.c. and a.c. motors. 8vo. 261 pp. *New York*, 1925

Broglie, M. de. X-rays. Translated by J. R. Clarke. 8vo. 217 pp. *London*, [1925]

Cady, F. E., and Dates, H. B., *editors*. Illuminating engineering. Prepared by a staff of specialists. 8vo. 499 pp. *New York*, 1925

Colebrook, F. M. Alternating currents and transients treated by the rotating vector method. 8vo. 205 pp. *New York*, 1925

Connan, J. C. Electrical estimating for industrial lighting installations. 8vo. 214 pp. *London*, 1925

Creighton, H. J. Principles and applications of electrochemistry. vol. 1, Principles. 8vo. 455 pp. *New York*, 1924

Croft, T. Circuit troubles and testing. 8vo. 234 pp. *New York*, 1924

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Hawkins, C. C. The dynamo: its theory, design and manufacture. 6th ed. vol. 3, Alternators. 8vo. 590 pp. *London*, 1925

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Institute of Marine Engineers. Papers on internal combustion engines [*By various authors*]. Read and discussed [1920]–1922. 8vo. 595 pp. *London*, *n.d.*

Irwin, J. T. Oscillographs. On the theory, construction, and use of electro-magnetic, hot-wire, electrostatic and cathode ray oscillographs. sm. 8vo. 176 pp. *London*, 1925

Kurtz, E. Substation operation. 8vo. 274 pp. *New York*, 1924

Lodge, *Sir* O., *D.Sc.*, *F.R.S.* Talks about wireless, with some pioneering history and some hints and calculations for wireless amateurs. sm. 8vo. 264 pp. *London*, [1925]

Luckiesh, M. Lighting fixtures and lighting effects. 8vo. 343 pp. *New York*, 1925

OBITUARY NOTICES.

WILLIAM ARNOT was born in Glasgow in 1854 and was educated at Hamilton Academy. He began his career as an engineer in 1880 when he came to London. From 1880 to 1892 he was in the employment of various companies, including the London Electric Supply Corporation and the India Rubber, Gutta Percha and Telegraph Works Co., Ltd., at Silvertown. In 1892 he was appointed the first engineer to the Electricity Department of the Glasgow Corporation, and he held that post until 1896. During this period the Electricity Department was under the control of a Sub-Committee of the Gas Department. The generating station at Waterloo-street, Glasgow, was designed and equipped by Sir Alexander Kennedy, under the superintendence of Mr. Arnot. As the demand for electricity continued to grow Mr. Arnot initiated and carried to fruition the policy whereby two large sites were acquired for new generating stations, one at Port Dundas on the north side of the River Clyde, and the other at St. Andrew's Cross on the south side of the river. Port Dundas station ultimately contained 38 000 kW of plant, and St. Andrew's Cross station 22 000 kW of plant. These two stations were gradually developed until they could accommodate no more plant, but they sufficed to meet the Glasgow demand until 1912, when the site of the Dalmarnock power station was acquired. Mr. Arnot resigned his post as chief electrical engineer to the Glasgow Corporation in 1897, when he commenced business as a consulting engineer in Glasgow. He acted as consulting engineer to the Govan Corporation, for whom he designed and equipped a complete undertaking, including a generating station with a plant capacity of 4 000 kW, and all the underground mains and cables. He also carried out a large number of private installations throughout England and Scotland, including Dunrobin Castle and Quarrier's Homes, Bridge of Weir, and his services were retained by the Town Councils of Wick, Lerwick, Brora and other towns in the north of Scotland. He also acted as consulting engineer in this country for the Rand Water Board, and carried out a large amount of inspection work for them both in Britain and on the Continent. Mr. Arnot was one of the pioneers in connection with the electricity supply industry, and foresaw the main features of the development of the industry which have taken place. He was a man of even temper, and of a quiet and retiring disposition, and he retained throughout his life the confidence and esteem not only of his large clientele but of his wide circle of friends in the industry. He died in Glasgow on the 25th June, 1925. He was elected a Member of the Institution in 1891.

W. W. L.

SIR WILLIAM F. BARRETT, F.R.S., died on the 26th May, 1925, in his 82nd year, and in him physical science has lost a devoted adherent and worker. He received his early education at the Old Trafford Grammar School, Manchester, and in 1863, when only 19 years of age, became assistant to the late Prof. Tyndall, Professor of Natural Philosophy in the Laboratories of the Royal Institution. Under this great master of science he must have received much stimulation of his natural taste of acquiring and increasing his scientific knowledge. In 1867 he was appointed assistant master at the International College, and was lecturer in physics at the Royal School of Naval Architects until 1873. His chief life's work was in connection with the Chair of Physics at the Royal College of Science, Dublin, which position he filled with much distinction for no less than 37 years, that is until 1908. He carried out his work there with great success, training many students of note. In 1899 he was elected a Fellow of the Royal Society and was knighted in 1912. He was one of the founders of the Physical Society of London in 1874, and along with Guthrie was chiefly instrumental in organizing that body. He also collaborated with Guthrie in fostering the summer courses for science teachers which the Science and Art Department originated in 1871. These courses were probably the first attempt to introduce the systematic teaching of practical physics and were attended by teachers from all parts of the country. He was a prominent member of the Royal Dublin Society, to which body he communicated several important papers, as he did also to the Royal Society and to the Institution. He was also a well-known figure at many of the meetings of the British Association, to which body he contributed interesting papers, and served on several of its committees. After his retirement in 1908 from the Chair of Physics at the Royal College of Science, Dublin, he still maintained his interest in scientific matters, frequently attending meetings of the Royal Society and other bodies.

The writer has been asked to communicate this brief appreciation of Sir William Barrett's life work, no doubt on account of his personal association with Sir William whilst research work was being carried out between the years 1896 and 1902. Regarding this work, the writer can bear the fullest and most cordial testimony to the great interest, time, labour and skill shown by the deceased scientist.

Sir William was greatly attracted by the work of Dr. G. Gore, F.R.S., who was probably the first to discover the peculiar behaviour of various specimens of iron which showed certain critical points during

heating and cooling. This led him to make further investigations and to his discovery of the peculiar behaviour and property, now termed "recalescence," in steel. It was largely due to these results that methods of examining various types of steel, each more or less possessing its own idiosyncracies, by preparing heating and cooling curves, were established. Between 1883 and 1902 the writer was discovering and developing his various new alloys of iron with other elements, and amongst other prominent scientists of those times, including engineers, electricians, metallurgists, chemists and physicists, with whom he came in contact and discussed his numerous researches on alloys of iron with other elements, was Sir William, whose acquaintance he first made in 1887. Sir William had a keen mind with a long and wide experience in carrying out experiments of a physical character, and he became intensely interested in the writer's many alloys of iron and carried out a large number of experiments on the magnetic, resistance, permeability and other electrical properties of the manganese steel discovered and made by the writer. These physical experiments and the results were described by Sir William in three papers to the British Association and the Royal Dublin Society, read in 1886–9. Subsequently the writer supplied a large number of specially prepared small specimens of his various alloys of iron with carbon, chromium, nickel, tungsten, silicon, aluminium and other elements in order that Sir William might test them in a similar manner. As a result, Sir William found that some of the alloys of iron and silicon, also of iron and aluminium, possessed valuable magnetic and electrical characteristics, including their low-hysteresis and high-resistance qualities. The results of such tests were described at length in joint papers by Sir William, Mr. (now Professor) W. Brown (who had assisted at the experiments) and the present writer, read before the Royal Dublin Society in 1899, 1902 and 1904, and also before the Institution in 1902. The important practical results which some years later were obtained and their service in the development of electrical equipment are too well known to call for more detailed mention here, but afford a striking instance of the value of co-ordination of the work of investigators in different branches of scientific research.

Sir William was elected an Associate of the Institution in 1881 and a Member in 1891. For several years he served on the Committee of the Irish Centre, of which he was chairman in 1901–02. R. A. H.

CHARLES ORME BASTIAN, eldest son of the late Dr. H. Charlton Bastian, F.R.S., was born in 1869 and died on the 29th October, 1924. Very early in life he developed a taste for mechanical pursuits. He studied at University College, London, and specialized in electrical engineering. On leaving there he was for some time with Messrs. Crompton and Co., Ltd. He was subsequently connected, as a director, with the Bastian Meter Co., Ltd., from the time of the company's formation until he retired in September 1916 in order to devote more attention to the development of his numerous patents, particularly in connection with electric radiators, ovens, water heaters, and the mercury-vapour lamp. He was the inventor of a thermal storage system in which a small electric current is allowed to flow continuously, the hot water being stored in a lagged tank or cylinder. This system was developed in co-operation with Lieut.-Commander F. J. Campbell Allen, of Messrs. Bastian and Allen, and shortly before he died Mr. Bastian was able to see the fruition of his labours in the large water-heating plant which he designed and installed in conjunction with that firm at Wick Lane Baths, Poplar, this plant being claimed to be the first successful one, on a large scale, in this country. He was elected a Member of the Institution in 1903.

F. J. C. A.

HENRY BEVIS was born in 1865 and died on the 16th July, 1925. In 1884 he joined Mr. (now Sir) Hugo Hirst as assistant in the Electrical Apparatus Co., Ltd. In 1886 Mr. Hirst left the firm to join with Mr. G. Byng in forming the General Electric Co., and Mr. Bevis continued to manage the Electrical Apparatus Co. In 1889, however, the company went into liquidation and Mr. Bevis then rejoined Mr. Hirst. He remained with him for 17 years, and in 1907 joined the firm of Pirelli, Ltd., in this country, which was then closely allied with the General Electric Co. He later became managing director of Pirelli, Ltd., and of the Pirelli-General Cable Works, Ltd., and held that position until 2½ years before his death. He took an active part in the inception and formation of the Electrical Trades Benevolent Institution and throughout his life took the keenest interest in its welfare. He was a firm believer in the value of the electrical exhibition and was always a popular and respected figure for his early efforts in this direction. In the early history of the General Electric Co. he made a tour round the world and also visited the Continent and the United States very frequently. In his time he was one of the best-informed men on trade in the electrical industry both at home and abroad. His colleagues and employees will remember him as a man of strong will and a forceful individuality in all matters of business, and they will also remember him as a staunch friend with many endearing and lovable qualities, and as a man with a big heart. He was elected a Member of the Institution in 1901. H. H.

GUSTAVUS FERDINAND BONNOR was born at Highbury on the 17th May, 1868, and was educated first locally and then at Frankfort. He died very suddenly during business hours at Westminster, from heart trouble, on Friday, 6th March, 1925. He served his apprenticeship with Messrs. Gwynne's of Hammersmith, later joining a firm of electrical contractors, whose branch at Bray he managed for some years. He was then appointed electrical engineer to the Bath Corporation, and in 1901 succeeded Mr. C. H. Wordingham as City Electrical Engineer at Manchester. On relinquishing this post he became interested in several mining projects in North Wales, and subsequently became chief engineer of the East Kent Colliery Co. During the war he was engaged on

Government work in connection with the manufacture of munitions. Returning later to consulting work he devoted his energies to research in connection with the production of cement from basic slag, and also designed and superintended the electrical equipment of several large sewage-disposal undertakings. A man of wide experience and great ability in his profession, he was an able mechanic and devoted much of his spare time to model making. Some examples of his skill in this direction have been presented to, and are now on view at, the South Kensington Museum. He joined the Institution as an Associate in 1890, and became a Member in 1897. During the war he changed his name by deed poll from Metzger, adopting that of his mother. F. P.

WILLIAM WALTER BRADFIELD, C.B.E., was the eldest son of William Bradfield, late of the General Post Office, and was born in London on the 18th March, 1879. He received his engineering education at Finsbury Technical College, and in 1897 joined Marconi's Wireless Telegraph Co., Ltd., at that time called The Wireless Telegraph and Signal Co., Ltd., as assistant to Senatore Marconi, and was thus associated with Marconi wireless telegraphy almost from its inception. He was engaged in wireless demonstrations on Salisbury Plain in 1897, and assisted in the erection of the Needles (Isle of Wight) wireless station. In 1898 he conducted a wireless service between Ladywood Cottage, Osborne, and the royal yacht "Osborne," when the late King Edward VII (then Prince of Wales) was confined to the yacht with an injured knee. In the same year Mr. Bradfield installed Marconi apparatus in the first British battleship to be equipped with wireless. He also had charge of a demonstration on board the U.S.A. battleship "Massachusetts." In the following year he assisted in the installation of Marconi wireless apparatus on the Borkum Riff light vessel and Borkum lighthouse. In 1901 he had charge of a demonstration for the French Government, of wireless working between Calvi (Corsica) and Antibes in the French Riviera. He was also responsible for the installation of the famous wireless stations at Siasconset (Nantucket Island) and on the Nantucket light vessel. Mr. Bradfield was appointed chief engineer of the Marconi Wireless Telegraph Co. of America in 1902. During his tenure of this office he attended the second International Radio Telegraphic Conference which met in Berlin in 1906. He returned to England in 1908 as deputy manager of Marconi's Wireless Telegraph Co., Ltd., and of the Marconi International Marine Communication Co., Ltd., and in 1910 became manager of both companies. In 1917 he was elected to the board of directors of both companies. During the war he devoted his entire energies to the support which the Marconi companies gave to the Services, and it was for this war service that he was appointed a Commander of the Order of the British Empire. For over a quarter of a century he was concerned with the development of wireless, particularly in connection with shipping, and it may be fairly stated that he was largely responsible for the efficiency of maritime wireless services and the high standard which they have now reached. In both business and social life he revealed a character which gained for him innumerable friends. His delightful personality endeared him to both business friends and colleagues, and his death leaves a sense of more than usual loss in those with whom he was associated. He was elected a Student of the Institution in 1897, and a Member in 1920. He was also a Fellow of the Institute of Radio Engineers (America), and an Associate of the American Institute of Electrical Engineers. He had been in failing health for some time before his death, but could not be persuaded to leave his work until the end of 1924, when he went to Switzerland for treatment; it was, however, too late, and he returned to London, where he died on the 17th March, 1925. A. G.

JOHN DANIEL LOVE BRADWELL was born on the 29th March, 1878, at Ashton, Lancashire, and died on the 19th August, 1925, at Solihull, near Birmingham. He was educated at Malvern College and Lausanne, Switzerland, and afterwards studied engineering at King's College, London, from 1896 to 1899. From there he went to Messrs. Ferranti, Ltd., as a pupil for two years, and stayed on with that firm for a further two years in their experimental department. He then obtained, in 1903, an appointment with Messrs. Willans and Robinson, Ltd., at Rugby, and was in charge of the electrical department of their testing shop. In November 1905 he left Rugby at the same time as Mr. E. A. Reynolds, who was also in the testing shop at Messrs. Willans and Robinson, and they commenced business at Birmingham in partnership, under the name of Reynolds and Bradwell, as electrical contractors specializing in factory equipment. He remained a partner in that firm until his death. In 1918 he was elected to the Council of the Electrical Contractors' Association, but had to retire soon after owing to ill-health, and subsequently was unable to take much active interest in business. He joined the Institution in 1903 as an Associate and was elected a Member in 1913. E. A. R.

ELLIS HERBERT CRAPPER, M.Eng., was born in Sheffield on the 24th June, 1861, and died at Rhos-on-Sea on the 22nd March, 1925, during a temporary absence from his home. He leaves a widow and one daughter. He received his early education at the Central School, Sheffield, and later was a student under Dr. Hicks, F.R.S., at the Firth College (now absorbed in the University of Sheffield). He also attended some of the special summer courses at the Royal College of Science, London. The whole of his subsequent career was spent in his native city. In early life he was a teacher at the Philadelphia Board School, from which he rose to the position of Peripatetic Science Master under the old School Board. At the end of the year 1889 he was appointed assistant master in the Junior Department of the Technical School (now absorbed in the University of Sheffield). Three years later he was transferred to the Senior Department, as Lecturer in Mathematics and Physics, and after the lapse of about another year he became Lecturer in

Physics and Electrical Engineering. On the formation of the University College he was appointed Lecturer in Electrical Engineering, and when the University was established in 1905 he became Senior Lecturer in Electrical Engineering, a post which he held for about 12 years, during which period the best part of his scholastic work was accomplished. In February 1917 his position was changed to that of Independent Lecturer in charge of the Electrical Engineering Department, a position which he occupied at the time of his death. He thus devoted the whole of his life to the cause of education, a pursuit which fitted him perfectly, and by his death in his sixty-fourth year the University, and especially the Applied Science Department, has sustained a very real loss. Not only was he a man of considerable attainment, a hard worker, unsparing of himself in lecture room and laboratory alike, but he possessed a genial and kindly personality, and was held in high esteem by both staff and students.

He was the author of the following books: "Electric and Magnetic Circuits," "Practical Electrical Measurements," "Arithmetic of Electrical Engineering," "Arithmetic of Alternating Currents," "Electric Circuit Problems"; and in addition he contributed numerous articles over a long period to the engineering journals. He made the testing of magnetic material his particular study, and during the war period was engaged in important magnetic tests in connection with magneto magnets and special nickel steels for the Aeronautical Inspection Department. Last year he wrote a series of articles entitled "The Elements of Magnetic Analysis," which appeared in *Engineering* and evoked favourable comment both at home and especially in the U.S.A. Many of the Sheffield steelworks, and also officials of the Indian Government, have sought his advice on the choice and testing of magnetic materials for special purposes. Apart from his scholastic attainments, he was a well-known figure in local Freemason circles, a Past Master of the St. Leonard's Lodge, and one of the founders of the University Lodge.

He was elected an Associate of the Institution in 1894, was transferred to Associate Membership in 1899, and became a Member in 1900. He was instrumental in the formation of what is now the Sheffield Sub-Centre and the Sheffield Students' Section.

C. H. H.

JAMES HUNTER GRAY, K.C., M.A., B.Sc., died unexpectedly after a relatively short illness on the 1st June, 1925. By his death the electrical industry especially, and industry in general, have lost one who was most enthusiastic in promoting development and progress, and in the exercise of his profession as a patent barrister his sympathies and efforts were ever in this direction. Born at Midcalder, Midlothian, on the 3rd September, 1867, he went at an early age to George Watson's College, Edinburgh; and on completing a successful school career he chose the scientific profession. He elected to study under the late Prof. Blyth, LL.D., of Anderson's College, Glasgow, a physicist and electrician of a high order and a model teacher. Mr. Hunter Gray, while specializing in mathematics and physics, educated himself in other directions in order that he might qualify himself for the degree of Bachelor of Science in London University. Part of this education was obtained as a summer-session student at Edinburgh University, and the remainder by home study and at Anderson's College.

After graduating at London University Prof. Blyth introduced him to Lord Kelvin, then Sir William Thomson, who admitted him to the physical laboratory in Glasgow University as a research student. While devoting the main part of his time to research and the study of higher mathematics and physics, Mr. Hunter Gray attended the usual Arts classes and graduated Master of Arts in the University, at the same time carrying on his research work in the laboratory. The results of some of this work were published in the proceedings of scientific societies and it may be useful to mention three * of these, as they are of interest to engineers. The first-mentioned is of special interest to electrical engineers concerned with wireless.

In 1891, the 1851 Exhibition Scholarships were instituted and Mr. Hunter Gray was nominated by Lord Kelvin as the University of Glasgow Scholar. The above-mentioned researches were carried out during the tenure of his Exhibition Scholarship. Towards the end of this period the well-known cordite patent action of Nobel *v.* Anderson was started and Dr. Bottomley (Lord Kelvin's nephew), who was retained by Nobels as a scientific witness, asked Mr. Hunter Gray to assist him with the experimental work on the case. He was thus brought into contact with Fletcher Moulton and other men then prominent at the English Bar. This case decided him to adopt the career in which he became so eminent. Not content with eating his dinners and studying law for his Bar examinations, he gained considerable knowledge of the practice of the law as a pupil in the office of a prominent firm of London solicitors before he was called to the Bar in 1895.

He was elected an Associate of the Institution in 1899 and became a Member in 1919. He served on the Council from 1915 to 1918, and his services were at all times freely available to the Institution. In this connection he served on several of its Committees, including that under Mr. Mordey on the 1919 Patents Act, where the assistance that he gave was most valuable. His work whether on committee or otherwise was most enthusiastically and unostentatiously done.

There are few patent actions reported during the last 25 years in which he was not prominent. It may be said that there was not a single action relating to electrical patents in which he did not appear as counsel and mostly in favour of the patentee. In addition, he acted for the Crown on many occasions on electrical accident inquiries, in cases under the Royal Commission on Awards to Inventors, sometimes for, and sometimes against, the Crown. He was intensely interested in his profession and in the technical subjects with which he had to deal. He took infinite pains to understand his case, and he was incapable of taking in argument

* J. HUNTER GRAY: "Slow Oscillations produced on discharging Electric Condensers of Great Capacity," *Report of the British Association for the Advancement of Science, Edinburgh*, 1892.

J. HUNTER GRAY and J. B. HENDERSON: "The Effects of Mechanical Stress on the Electrical Resistance of Metals," *Proceedings of the Royal Society*, 1893.

J. HUNTER GRAY: "On a Method for determining the Thermal Conductivity of Metals, with applications to Copper, Silver, Gold and Platinum," *Proceedings of the Royal Society*, 1894.

what he considered to be a bad point. In his conduct of a case, whether as examiner or cross-examiner, he always followed a definite line which he had planned beforehand so as to develop his case as shortly as possible, and in summing up he was brief and concise, in many cases too brief to satisfy the eager client, but more often than otherwise he achieved the result that he and the client desired.

Mr. Hunter Gray, or "Jimmy" as his many friends and intimates called him, was not only eminent and popular in his profession but his lovable disposition and character endeared him to all with whom he came in contact. One cannot better the estimate of the impression which he made on his fellows than that which is contained in the following extract from the beautiful tribute to his memory by Lord Hewart, the Lord Chief Justice, in *The Times* of the 6th June:—"But if 'Jimmy' had a genius for law and a genius for advocacy, he had also something far more important than either or both—a genius for friendship. No man was ever more beloved by those who knew him. He had not one enemy. While there was nobody who spoke, or had occasion to speak, one word against him, his praises were on all men's lips, as they are to-day when we miss him and deplore his loss—the staunchness and tenderness of his friendship; the complete lovableness and simplicity of his character; the playfulness and humour which, while they revealed the heart of a child, drew all children to him; the unselfishness and generosity which were not so much characteristics of his life as the very essence of his life itself."

OLIVER HEAVISIDE, F.R.S., the first Faraday Medallist of the Institution, was an eccentric genius, such as occur from time to time in the history of science and the arts, one of those who seem to have a native faculty either of understanding recondite matters or of doing things which to ordinary people are inexplicable, and yet who find it difficult to mix with their fellows, and have less than a competent grip on the ordinary affairs of life. Puzzling psychical problems are not unknown. An infant prodigy presents a problem not easy of solution. A child is sometimes found who can play a musical instrument without having gone through the drudgery of learning, or who has an innate faculty for arithmetical calculation. We can hardly tell whence such a faculty arises, nor what may be its result. That Oliver Heaviside was a prodigy of this class there is no evidence to show. Details of his youth are unknown to the public. He would seem to have been an ordinary telegraph operator when first known, but one who developed a surprising mathematical faculty without apparently adequate cause and to whom the details of recondite electrical theory seemed simple and obvious. He had not the advantages—or, as he might have said, the disadvantages—of a Cambridge training; and his mathematics were not of the Cambridge type. It may be that they were more of the German type; but there is no reason to suppose that he learnt them in Germany, nor is it easy to say where he learnt them. His treatment of science had idiosyncrasies of its own; and he seemed to know intuitively what most able people have to spend years in learning. The result was that for some time his writings were difficult to read and were for the most part unappreciated by orthodox mathematicians; whilst to many electricians they seemed in the clouds, with no likelihood of practical application to the affairs of earth.

He is not to be put on a level with Clerk Maxwell, who grasped the experimental facts discovered by Faraday and threw them into mathematical form so as to deduce from them by regular process their intimate meaning and vital and important consequences. He was rather one who absorbed the views of Clerk Maxwell, apparently without effort, and applied them in his own way with further elaboration and results. In the "Electrical Papers," which for many years were published in the *Electrician* and were collected in two volumes under that title, he covered a great part of electrical science after his own manner; and in his subsequently-produced three volumes on "Electromagnetic Theory" he collected those which had a special bearing on telegraphy in its widest sense, and developed them with special attention to the new theory of electric waves.

Everything that concerned the interaction of ether and matter must have had a fascination for him. He absorbed (after his own fashion) the essence of Poynting's theorem about the way in which electric and magnetic fields were interlocked, and how their interaction inevitably resulted in locomotion—whether the free locomotion of something with the speed of light, which we are familiar with as radiation without exactly knowing what it consists of, or the more constrained locomotion of matter under electromagnetic influence, which is equally familiar in dynamos and electric motors. He knew no more than the rest of us what the etheric modifications called an electric field, on the one hand, and a magnetic field, on the other, really consist of; but he recognized an electric charge as a peculiar modification of the ether, and devoted himself to the problem of what happens when an electric charge is made to move, thereby developing or exhibiting magnetic effects.

A great part of the theory of electric waves was elaborated in more orthodox fashion by Hertz; but Heaviside pursued the subject into remarkable detail, and recognized that these waves constituted the foundation for electric telegraphy of all kinds. He drew no distinction of a fundamental kind between radio telegraphy in free space and the other kind which is guided by conductors: to him the processes were fundamentally the same, and only modified by artificial arrangements and special constructions. He thus approached telegraphy from what may be called the "wave" end, emphasizing from the beginning the vital importance of what was known as self-induction; he elaborated the influence of the two great and still unknown etherial constants, and he thus gave the theory of telegraphy in its most general and comprehensive form.

To enter into a little more detail. The achievement which first brought him into effective notice was the fact that he extended and supplemented Lord Kelvin's original theory of cable telegraphy (which so far had

been conducted on the lines of Fourier's theory of the conduction of heat), by introducing the factor of inductance or self-induction, which up to that time, so far as it has been attended to at all, was regarded by practical telegraphists as a bugbear or a nuisance to be got rid of or eliminated as far as possible. He showed that Lord Kelvin's diffusion theory was very incomplete, and that by attention to the ignored factor it might be possible to attain much better results. In fact he gave the complete theory of cable and all other telegraphy, showing that in every case it depended on waves travelling through the ether, which were guided but at the same time modified, smoothed out, attenuated and distorted by material substances, especially by the conductors which were used to guide them to their destination. Fortunately, Lord Kelvin—though he never apprehended electric waves to their full extent and was doubtful about many points in Clerk Maxwell's theory—was able to recognize that his diffusion theory was incomplete and that Heaviside had made a great step in advance. He recognized fully that Heaviside's theory of cable signalling was more complete than his own; and his recognition did much to introduce Heaviside to the knowledge of the wider electric world.

Before that time only a few—such as FitzGerald and Lodge and Searle and Perry—had seen any possible useful meaning in Heaviside's rather eccentric lucubrations, Perry having been attracted to them by the ingenuity of some fractional differential operators like $\sqrt{(d/dt)}$ which were known to pure mathematicians like Henrici but which had not been applied to physical problems. But Heaviside's ambition was that his work should be recognized not merely by mathematicians, with whom he probably felt himself on equal terms, but by practical telegraphists; for he saw that his mode of regarding the facts, and his completer theory, must in the long run have a revolutionary effect on telegraphic and especially telephonic transmission. So he was bitterly disappointed when British telegraphic authorities, headed by Sir William Preece, who regarded his notions as absurd, caused his papers and those of his brother A. W. Heaviside—who, still engaged in northern telegraphic enterprise, sought to put them into concrete and practical form—to be rejected by the Society of Telegraph Engineers. For what he regarded as the ridicule thus cast upon his work by practical men he never forgave Sir William Preece, and throughout his subsequent writings there occur sarcastic references to those in authority who were unable to recognize the truth of what specially concerned their art. He even managed to introduce these sarcasms, in a veiled form—so veiled as to seem inoffensive and probably unintelligible to the editor and other readers—into the concluding portion of his article on the "Theory of Telegraphy" in the tenth or supplementary edition of the "Encyclopædia Britannica."

That Heaviside's theory has now been applied on an extensive scale both to sea and land telegraphy and telephony—especially perhaps in the United States under the auspices of the Western and the General Electric Companies—we all know. Among the first to take the theory up and seek to make it practical was Silvanus Thompson in this country and, with considerable success, Dr. Pupin in America. The main feature is the purposed introduction of that bugbear of old telegraphists, self-induction, in order to give momentum to the waves and thus counter the deleterious influence of resistance and capacity. Heaviside knew well enough that if the dissipation of energy by metallic resistance could be abolished, transmission would be easy and distortion reduced to zero. That is what constitutes the great advantage of radio or wireless telegraphy: the waves are there travelling in a perfectly transparent medium, without resistance or absorption of energy, nothing but mere attenuation with distance; and accordingly every feature of the wave is preserved, so that they arrive just as they were sent, waves of all lengths travelling with the same speed, and the shape or features of the waves are maintained intact, as good as new, even though the amplitude or energy might be reduced to a millionth or a billionth of what it was at the start. The essence of the problem is that the electric and magnetic energies must be maintained equal, as the essential condition for a true wave. Any absorption of current or magnetic energy, leaving one factor stronger than the other, would begin to reflect part of the wave back upon itself, would cause different harmonics to go at different rates, and the features would accordingly be smoothed out, as a coach spring smoothes out the irregularities of a road. Elasticity and friction were the deleterious elements: momentum is needed to counteract them; and this momentum, which in the ether is of a magnetic character, could be provided in cases where resistance and capacity were inevitable, by the introduction of induction coils at short enough intervals, or by the continuous increase of inductance, as by coating a copper conductor with a sufficiently permeable coat of special quality iron. In that way the lost magnetic energy could be replaced, and the two energies still kept more nearly equal.

The writer has dealt at some length with this matter, which doubtless is now fairly familiar to electrical engineers, because of its practical interest and importance; but the theory of electrical waves, as given especially in Heaviside's third volume, may ultimately turn out to have features of still more absorbing interest. It is too soon as yet to realize the bearing of his writings on the theory of the ether, a theory to which Sir Joseph Larmor, Lord Kelvin and G. F. FitzGerald have in their own way so powerfully contributed, and which has since been extended by Planck and Einstein and Eddington and Jeans, without (in some cases) explicit recognition of what the ultimate bearing of their theories will be. Meanwhile that article in the "Encyclopædia Britannica" above referred to, which is reproduced in Heaviside's third volume of "Electromagnetic Theory," is a wonderful summary of electromagnetic doctrine; a little puzzling in places, as usual, because of his mode of expression, but exhibiting a comprehensive grasp of the main features of the problem, and a clear statement of what is at present known, such as few others would have been able to put in so small a compass.

Not only in this country but rather specially on the Continent and in America has Heaviside's work been appreciated, and even his reformed nomenclature often adopted. For instance, Professor H. A. Lorentz in his admirable lectures in 1906 on "The Theory of Electrons" (published in this country in 1909) says concerning Maxwell's equations: "We shall not use these formulæ in the rather complicated form in which they can be found in Maxwell's treatise, but in the clearer and more condensed form that has been given them by Heaviside and Hertz." Then he goes on to approve Heaviside's crusade against what he called the eruption of 4π's, due to the original statement by Coulomb of the force between two charges, with r^2 in the denominator instead of $4\pi r^2$—which would have been better, since e and m would have then given the total number of lines of force, instead of the lines through unit angle; and 4π would have been eliminated from a great number of equations if it had been introduced in its simple and natural place. So Lorentz goes on: "In order to simplify matters as much as possible, I shall further introduce units of such a kind that we get rid of the larger part of such factors as 4π and $1/(4\pi)$, by which the formulæ were originally encumbered. As you well know, it was Heaviside who most strongly advocated the banishing of these superfluous factors, and it will be well, I think, to follow his advice." This may seem a small matter, but a practical appreciation by so great a man as Prof. Lorentz could not fail to be gratifying, and is typical of the widespread recognition of Heaviside's work, which, delayed through many impecunious years, did ultimately begin during the later portion of his life.

The facts of Oliver Heaviside's life have been recorded elsewhere, and may here be reproduced as this is an obituary notice. The writer's own personal appreciation of him will be found in the *Electrician* (1925, vol. 94, p. 174), and on page 186 of the same number will be found a portrait, the only one known to exist.

Concerning his work as a young man, Mr. W. Brown writes as follows: "As a junior telegraph clerk I worked with Mr. O. Heaviside in 1868. He was then a young man and was employed by the Danish Cable Co. (the Great Northern Telegraph Co.) as telegraphist. The cable was terminated in, and operated from, the office of the United Kingdom Telegraph Co.—the pioneer of the shilling rate—in Queen-street, Quayside, Newcastle-on-Tyne. Wheatstone apparatus was used, and it was on that circuit, Newcastle-on-Tyne to Jutland, where I made my first acquaintance with that system. Oliver Heaviside was the principal operator at Newcastle—appointed no doubt by the influence of his uncle, Sir Charles Wheatstone. He was usually on day duty. He was a very gentlemanly-looking young man, always well dressed, of slim build, fair hair, and ruddy complexion. I think he was there until the transfer, after which the cable company rented a room adjoining those occupied by the Post Office, wherein the combined plant of the acquired companies was concentrated. The cable telegrams were then passed through a hatch in the doorway separating the premises and the staffs, and from that time I lost sight of Oliver Heaviside. My next recollection of him was when he emerged as a mathematician."

The following biographical facts are taken from portions of an excellent obituary notice in *Nature* of February 14th, 1925, by Dr. Alexander Russell:

"Heaviside was born in London on May 13, 1850. After leaving school he obtained a post with the Great Northern Telegraph Co. at Newcastle-on-Tyne, which he held for several years. During this period he communicated papers to the *English Mechanic*, the *Telegraphic Journal* and the *Philosophical Magazine*. These papers are of more than average ability and show great promise. For example, in 1873 he showed that quadruplex telegraphy was a possibility. He published many papers, which gradually became more and more technical and more and more difficult to understand, as it became necessary, in order to avoid repetition, to assume that the reader knew some of the writer's previous work. Consequently he had difficulty in getting them published in the ordinary technical journals. He had, moreover, to run the gauntlet of a good deal of unintelligent criticism, and none of his discoveries received that immediate recognition which their merit deserved. Heaviside communicated to the Society of Telegraph Engineers (now the Institution of Electrical Engineers) a paper solving the problem of the electrostatic and electromagnetic interference between overhead parallel wires, a problem which has come to the front at the present time. His methods of measuring mutual inductance, published in 1887, are of great value in themselves, and, like most of Heaviside's work, have been most fruitful in suggesting extensions to others. He was the first to solve the problem of the high-frequency resistance and inductance of a concentric main. It would probably have remained neglected for many years had not Kelvin given some of his results in his presidential address to the Institution of Electrical Engineers in 1889. From the practical point of view, Heaviside's most important work was laying the foundation of the modern theory of telephonic transmission. His theory of the distortionless circuit showed clearly the lines on which telephony could be developed. Working on these lines some ten years later, Prof. Michael Pupin in the United States developed his loading coils, and long-distance telephony was born. In 1891 Heaviside was elected a Fellow of the Royal Society. In 1892 his earlier 'Electrical Papers' were published in two volumes. The value of his work began then to be realized by electricians. He did perhaps more than any man to show the value of a knowledge of physics and of mathematical theory in the electrical industry. Pupin has said that Heaviside did much 'to introduce the living language of physics in place of the sign language of mathematical analysis.' The first volume of Heaviside's great work on 'Electromagnetic Theory' was published in 1893 and the second in 1899. His original intention was to publish the third volume in 1904 and the concluding volume in 1910, but this he found impossible, and so published the third and concluding volume in 1912. Heaviside was the first to give the theory of the steady rectilinear motion of an electron through

the ether, a theory which has been developed by others—notably by Searle—with important results. He was one of the first to predict the increase of mass of a moving charge when its speed becomes very great. To verify all Heaviside's reasoning, and especially to examine the validity of some of his mathematical methods, will provide work for many mathematicians and physicists. Many theorems given in his article on the 'Theory of the Electric Telegraph' in the "Encyclopædia Britannica" are constantly quoted by the writers of textbooks. In particular his description of what is now called the 'Heaviside layer,' by means of which Hertzian waves are supposed to be bent round the earth, is familiar to every radio engineer. In the later years of his life Heaviside was one whom every electrical engineer delighted to honour. In 1908 he was elected an Honorary Member of the Institution of Electrical Engineers. When in 1921 the Faraday Medal was founded, it was universally considered most appropriate that Heaviside should be the first Faraday medallist. The president, Mr. J. S. Highfield, went to Torquay and presented it to him in person. He was an honorary Ph.D. of Göttingen, an honorary member of the Literary and Philosophical Society of Manchester and of the American Academy of Arts and Sciences. For fifty years Heaviside lived practically a hermit's life in Devon. He was a good correspondent, but very difficult to approach personally. In his later years Dr. and Mrs. Searle, of Cambridge, were practically his only friends. The Government gave him a Civil List pension, and about twenty years ago Mr. Asquith increased it. The Institution of Electrical Engineers took a filial interest in him, and it is gratifying to remember that during the last few years of his life the Institution kept in constant touch with him. In the preface to his 'Electrical Papers' he says that the question 'Will it pay?' never interested him. He died at Torquay on Tuesday, February 3 (1925), and was buried on Friday, February 6, in the same grave as his father and mother; only relatives, and Mr. R. H. Tree representing the Institution of Electrical Engineers, being present. Thus ended the life of one who has left a record of work which has proved of great value to the world."

O. L.

ARTHUR JACOB died at his home at Hatch End, Middlesex, on the 3rd April, 1925, at the age of 57 years. He was the son of Archibald Hamilton Jacob, aurist, of Dublin, and received his technical education at the Royal College of Science, Dublin. His early experience was gained under Dr. S. Z. de Ferranti, then engineer-in-chief of the London Electric Supply Corporation, Ltd.—the first company in London to undertake the supply of electricity for lighting and power purposes. Mr. Jacob was assistant engineer with this company for five years, having successively charge of their mains, substations and Deptford power station; this plant, as is well known, was at the time an unique example of the possibilities of economic power distribution by the use of large units (1 500 h.p.) and high pressure (10 000 volts). Mr. Jacob's later experience included the position of resident engineer to the Electricity Supply Co. for Spain, Ltd., at Madrid. Subsequently, as chief resident engineer to the British Thomson-Houston Co., Ltd., he was responsible for the conversion of the entire Dublin United Tramways system from horse to electric traction, the contract including the erection of two power stations and substations for the supply of polyphase and direct current for the operation of 300 cars on 42 miles of track. On completion, Mr. Jacob operated this system for a period of three months before handing over. Later, as general manager of the British Schuckert Electric Co., he was responsible for traction, power and lighting schemes for the Corporations of Paisley, Coventry, Southampton and Birmingham, respectively, as well as for the Dunlop Rubber Co. and numerous other municipal and private undertakings. On the acquisition of the British Schuckert Electric Co. by Siemens-Schuckertwerke, Berlin, Mr. Jacob joined Siemens Brothers and Co., Ltd., and upon the formation by that company of Siemens Brothers Dynamo Works, Ltd., undertook the management of the latter company's central station department. In January 1908 he became a member of the management of the British Aluminium Co., Ltd., aluminium producers, and until the time of his death was charged with the development of the use of aluminium for industrial purposes in general, and electrical purposes in particular; in later years he also directed certain of the company's subsidiary undertakings. Mr. Jacob was a member of the Overhead Transmission Line Materials Committee of the British Engineering Standards Association; also a member of the Overhead Wires Committee of the British Electrical and Allied Industries Research Association. In addition to being a Member of the Institution he was a member of the American Institute of Electrical Engineers and the American Electrochemical Society, an original member of the Institute of Metals, and a member of Executive of the Federation of British Industries, the British Engineers' Association, the Industrial League and Council and other organizations. To his colleagues, as well as to a large circle of friends and acquaintances in this and other countries, the untimely death of Mr. Jacob brought a distinct sense of loss. A man of no mean powers, he combined with these a soundness of character, an attractive personality, warm sympathies and a ready wit, establishing in the course of years an extensive personal connection in the engineering industries. He was elected a Member of the Institution in 1901.

W. M. Mn.

WALTER LANGDON-DAVIES died in December 1924 at the age of 57 after a long and painful illness. Although his life cannot be described as one of material success, yet there are not a few in the electrical world who will recall him for many years to come as an active and eager pioneer who broke new ground, occasionally for his own purposes, but more often to clear the path for others. He received his scientific education at the School of Mines, now the Royal College of Science, at South Kensington. His first work was under his father, Charles Langdon-Davies, who was at that time developing the phonopore, a telegraphic system

of the von Rysselberg period. While engaged on this he devised the induction motor, which was later brought out by a company bearing his name. For some years he was the technical director of this company. Afterwards he went to Vancouver, where he worked as a consultant with the great power distribution company of British Columbia. On his return to England he devoted himself to electric welding, and the Daysohms Welding Co. was formed to develop his inventions. With this company he was connected until his death. So bald a record of his activities must seem to those who knew him an inadequate reflection of the absorbing passion for electrical discovery which animated him almost to the exclusion of any other interest. Nor was his method of research that which is in favour at universities and places where they proceed by careful induction. "With him it was always instinct," writes a friend, "and instinct nearly always right; then experimental proof; then theory; and, last and least, reward. He had more scientific curiosity and enthusiasm than anyone I ever knew." It was as he lay in the last few months on his bed of pain that he formed the determination to leave his body, racked as it was with cancer, for purposes of research, and the present writer recalls the enthusiasm with which he said one day that this was the future life to which he looked forward and, since otherwise he was now useless, the sooner the new life began the better. He was elected a Member of the Institution in 1919.

B. N. L.-D.

ANDREW BRUCE MACLEAN was born in Glasgow in 1856 and died on the 17th May, 1925. Educated in Glasgow, he left school early to take up a career of commerce. While still a boy he joined the Glasgow agency of the India Rubber, Gutta Percha and Telegraph Works Co., Ltd. (the Silvertown Company), then under the management of the late Mr. Matthew Gray. His business aptitude and alertness were quickly recognized by Mr. Gray, and rapid promotion followed. While still in his early twenties he was appointed to the Silvertown agency in Sheffield; this was followed a few years later by the similar post in Birmingham, and in 1890 he returned to Glasgow to take charge of the Silvertown agency in his native city. He continued with the company until 1897, when he founded the Craigpark Co., Ltd. Five years later the need for expansion of premises, and of the business generally, called for further capital. A suitable factory was found in Springburn, and the new company, the Craigpark Electric Cable Co., Ltd., of which he was managing director until his death, absorbed the original company. His tireless energy, fearlessness, grasp of detail and an unusually quick and active mind soon led the company through the troubled waters of its early years. The electrical trade loses one of its oldest members; probably no one at the present time can claim to have been in the trade for 54 years. In Scotland at any rate he was, from the commercial point of view, a real pioneer, and he was probably the first to attempt to sell telephones for use in offices and factories, and this at a time when exchanges had not been thought of. His geniality and kindliness endeared him to a large circle of friends, who were quick to appreciate his sterling qualities of heart and mind. He was elected a Member of the Institution in 1904.

M. M.

WILLIAM LEONARD MADGEN died in January 1925 at the age of 63 years. He was a pupil in the School of Electrical Engineering, Hanover-square. He then joined the Telephone Company, and in 1882 went to Belfast as district manager; a little later he joined Woodhouse and Rawson as one of their departmental managers. Between 1888 and 1891 he was associated with Mr. Manville (now Sir Edward Manville) and with Mr. Statter. In 1892 he co-operated with the late Robert Hammond in establishing the journal *Lightning* (now the *Electrical Times*). In 1893 he was engaged in developing the Ferranti meter business. During the next three years he was occupied with propaganda relating to the maximum demand system of charging for electricity, introduced by Mr. Arthur Wright. In 1896 he did important work in connection with the formation of the Municipal Electrical Association. He and the writer thus approached the development of the electrical industry from opposite poles. He was at first a strong advocate of municipal trading; but he changed his views, notwithstanding his close association with municipal authorities, and became a supporter of the Industrial Freedom League, formed to show the unwisdom of developing the electrical industry on parochial lines. In 1900 he was busy promoting electrical power Acts; his paper and the discussions before the Institution on this subject, published in the *Journal*, constitute interesting landmarks in the development of the industry. When in 1897 the Electrical Power Distribution Co. was formed, no outside capital could be raised for the enterprise; for even the writer's financial group regarded it as too speculative. The pioneering work of this company required several years of hard work without profit; some time later the British Electric Traction Co. absorbed the E.P.D. Company, and Mr. Magden became a director of the B.E.T. Company. His ideas of business were tempered by social views prompted by genuine, not political, desire to ameliorate the conditions of the masses, as is shown by his paper on "Industrial Distribution: the Crux of the Overcrowding Question" (*Journal of the Royal Society of Arts*, 1902). In his schemes he aimed at symmetry and completeness not generally attainable. This is seen in the titles he adopted. For instance, a little lighting company for Lewes was called the County of Sussex Company. He had a friendly emotional disposition, with a keen sense of justice. He could easily forget as well as forgive unintentional injuries, but he would never forgive the sins of insincerity. Unfortunately, he did not sufficiently organize his activities on matters outside business to obtain the diversion which intense application to responsible work required. He was elected an Associate of the Institution in 1881, and a Member in 1890.

E. G.

WALTER MARKBY was born in London in 1865 and died suddenly from heart failure at his home in

Paddington on the 29th November, 1924. He was apprenticed at the North London Railway Works, going through the fitting shop and drawing office, and went direct from there, in June 1890, to the Metropolitan Electric Supply Co. under Mr. Frank Bailey. He remained all his life in the service of this company. Starting in the drawing office, he transferred as an engineer in charge of the old underground generating station at Whitehall to Manchester-square station in 1892. In 1893 he became superintendent engineer at Whitehall Court and in 1894 superintendent at the company's Amberley-road station, being in 1902 transferred to the main generating station at Willesden as superintendent and, upon the retirement of Mr. J. S. Highfield in 1916, was appointed chief engineer of the company, which position he held to within a few months of his death. Owing to an accident when very young, he was rendered permanently lame. He was a man of very retiring disposition, whose every effort was centred in his work; consequently he was not very well known to the electrical profession. That he was extremely kindhearted and greatly esteemed by his employees was evinced by the fact that every man who could be spared attended the memorial service held in St. Saviour's Church, Paddington, upon the occasion of his funeral. He was elected an Associate of the Institution in 1891, an Associate Member in 1899, and Member in 1905. A. F. H.

THOMAS COMMERFORD MARTIN was born in London in 1856 and when quite young went to America, where from 1877 to 1879 he was associated with Edison in electrical development. In 1883 he was appointed editor of the *Electrical World* and held that position for seven years, resigning to assume the editorship of the *Electrical Engineer*. In 1899, when the *Electrical World* came under the control of the McGraw-Hill Publishing Co., which also purchased the *Electrical Engineer* and amalgamated the two papers, Mr. Martin again became editor of the *Electrical World*, holding this post until 1909. In addition to contributing on electrical subjects to periodicals, he wrote a number of books, amongst these being "The Electric Motor and its Applications," "Inventions, Researches and Writings of Nikola Tesla," "Edison—His Life and Inventions" (in collaboration with Mr. F. L. Dyer), and "The Story of Electricity" (in collaboration with Mr. S. L. Coles). Mr. Martin was elected a Foreign Member of the Institution in 1891 and a Member in 1911. He served as President of the American Institute of Electrical Engineers in 1887 and as executive Secretary of the National Electric Light Association from 1910 to 1919. He died on the 17th May, 1924, at the age of 67.

HARRY BRYANT MATTHEWS was born in 1876. His engineering training was acquired partly in works, and partly in university classes. He attended as a full-time student at two universities, but did not in either case fulfil all the conditions necessary for gaining a degree or diploma. His technical training was, nevertheless, most thorough. He spent two years—1902 and 1903—at the Birmingham University as a research scholar, after winning in open competition the Bowen Research Scholarship. During those two years he devoted a good deal of time to research work on single-phase motors. In September 1903 he was appointed senior lecturer in electrical engineering at the Birmingham Technical School, and remained on the staff there for nine years. He was an able and efficient teacher and showed much initiative in devising new and valuable laboratory arrangements by means of which large evening laboratory classes of an advanced grade could be efficiently dealt with. He was very fond of teaching, was always kindly and sympathetic with his students, and proved to be a most successful head of an electrical engineering department. He was enthusiastic, and had many other attractive social characteristics which caused him to be much liked by all who came in contact with him.

He was elected an Associate Member of the Institution in 1905 and a Member in 1913, and took an active part in the discussions of the Birmingham Local Section, now South Midland Centre, but he had little ambition to write formal papers describing his own experimental work. His chief contribution is to be found in Volume 40 of the *Journal*, and describes some of the results which he obtained on the distribution of magnetic flux in the air-gaps of machines having slotted armatures. He acted as Honorary Secretary of the Birmingham Local Section from 1906 until he left for India in 1912. He did excellent work for the Institution in this capacity, and was highly esteemed by his fellow members.

He took a great interest in the Territorial movement. In 1908 he energetically assisted in raising the Telegraph Companies of the Southern Command. He held the rank of Captain of the Wireless Section, and was the first officer serving in that capacity in the Midlands. His extensive personal acquaintance with young electrical engineers, due to his two positions as a teacher in the Technical School and as Honorary Secretary of the Local Section of the Institution, enabled him to exert considerable influence in recruiting for the Corps in the days shortly before the war. In 1912 he was offered, and accepted, the post of Assistant Professor of Electro-technology at the Indian Engineering Research College, Bangalore. Later he became Professor of Electrical Engineering at the College of Engineering, Guindy, Madras. He returned to this country in February 1921 on medical leave, owing to a nervous breakdown brought on by overwork, and did not recover sufficiently to take up his work again. He died in the summer of 1925. W. E. S.

ALFRED ERNEST MILLS, M.A., died on the 15th August at North Finchley at the age of 61. He was educated at University College School, London, and Clare College, Cambridge. Owing to ill-health he did not follow an active engineering career but always took a great interest in the progress and development of the science. In 1887 he was appointed Assistant Secretary to the Railway Benevolent Institution, and in 1898 became General Secretary. He held that position for 27 years, eventually retiring at the end of 1924 owing to failing health. He was elected an Associate of the Institution in 1885 and a Member in

1887, and was also a Fellow of the Physical Society of London. G. M.

JAMES PIGG died on the 8th July, 1925, aged 68 years, after a few days' illness and an unsuccessful operation. He joined the Institution as an Associate in 1893, became an Associate Member in 1899, and a Member in 1907. His association with electrical work began with some of the earliest applications of electricity when, as a boy, he started work in the signals department of the Stockton and Darlington Railway. By steady application he rose to the position of inspector of a district, obtaining the elements of his theoretical training by evening study at the Durham College of Science, now Armstrong College, Newcastle-on-Tyne. After the amalgamation which formed the North-Eastern Railway, when the company began, in 1891, to introduce electric lighting and power, he was selected to supervise the work. He was intimately connected with all electrical developments on that railway from that time until his retirement, and from 1901 held the position of Electrical Superintendent. During that period the electrical work on the railway developed from an annual consumption of one million units to 28 times that amount. Although the heavier applications of electrical energy formed the major portion of his later work, he still retained a keen interest in railway signalling. This was to some extent inherited, for his father was a signal inspector, and it was characteristic that, when in 1898 he published a book on "Railway Block Signalling," the title page carried the dedication "To the Author's Father, an I.O.U." This book was the first in this country dealing exclusively with the principles of train signalling and apparatus for ensuring safety.

He contributed frequently to the electrical journals, and read several papers before the Institution in London and at Newcastle-on-Tyne. His masterly paper on the problems of locomotive cab-signalling will be long remembered by those who heard it delivered.

He served on the Committee of the Newcastle Local Section (now North-Eastern Centre) for several periods, and was chairman of the Section during the session 1907–8. He retired from active work on the railway at the end of 1922 after 51¾ years of service, and his death occurred when the centenary of this, the first, railway was being celebrated.

He was a shining example of a man who, having risen to a high position by his own unaided effort, was still quite unspoiled by success. It was said of him by one who was to some extent antagonistic to him in his earlier days, but who afterwards became one of his staff, "I never before had such a fine man as my chief."

F. O. H.

SIR DAVID LIONEL GOLDSMID STERN SALOMONS, BART., M.A., died on the 19th April, 1925, at the age of 73. He was the only son of Philip Salomons of Brighton, and grandson of Sir Jacob Montefiore of Sydney, New South Wales. From University College, London, he went up to Cambridge and took a 2nd class in the Natural Science Tripos in 1873. In the same year he succeeded to the baronetcy of his uncle, Sir David Salomons, the Liberal Jew who made a long fight for admission to the House of Commons, and was the first of his faith to sit there. He was called to the Bar by the Middle Temple in 1874. He was a magistrate and Deputy-Lieutenant of Kent, and was High Sheriff in 1881. In 1882 he married a daughter of the late Baron Hermann de Stern, a sister of the first Lord Michelham. Sir David was one of the oldest members of the Institution, having joined the Society of Telegraph Engineers in 1875, only four years after its formation. It was on his proposal that the Institution was formed from the old Society. He was a member of the Council and Honorary Treasurer for many years, and became a Vice-President. There is little doubt that if he had been a practising electrical engineer instead of a distinguished amateur he would have occupied the Presidential chair. He generously perpetuated his interest in and connection with the Institution by endowing the scholarship which is named after him.

He took great interest in practical electrical applications all his life, and established a laboratory and workshop at Broomhill, his seat near Tunbridge Wells, where he did a great deal of experimental work. He claimed to be the first person in this country to light his house by incandescent electric lamps—that was in 1874, when all the accessories were home-made. His book on "Electric Light Installations and the Management of Accumulators," based on his own practical experience, was one of the first on the subject. It passed through many editions. He was a director and the first chairman of the City of London Electric Lighting Co., Ltd. His interests were many and varied. He was a director of the South-Eastern Railway, and on its amalgamation with the other two lines he became a director of the Southern Railway. He was one of the pioneers of the motor-car. It is related that when he performed the opening ceremony of the electricity station at Tunbridge Wells—about 30 years ago—he arrived from Broomhill with Lady Salomons in a motor-car, which by law was not allowed to travel on a public road at more than a walking pace and was preceded by a flagman. At a very early period he made and used home-made electric carriages. He organized the first motor-car exhibition—at Tunbridge Wells—and took a prominent part in the larger exhibition held shortly afterwards at the Crystal Palace. At a meeting convened by him the Self-propelled Traffic Association was formed. As its first president he initiated and carried to success the movement to induce the Government of the day to pass a measure removing the restrictions on such traffic. He was one of the founders and an honorary member of the Automobile Club de France, and a founder and honorary president of the Aero Club de France.

He was greatly interested in early time-pieces, of which he had an important collection, including many examples of the work of Breguet. He wrote a life of Breguet which was republished in a French edition for the centenary of that famous French watchmaker. His continued interest in electrical matters as well as his kindliness is shown by his having till the last remained president of the Electrical Trades Benevolent Institution.

He leaves a widow and three daughters. His only

son, Capt. David Salomons, was drowned on service in the Hythe disaster in 1915. W. M. M.

HERBERT WATSON SULLIVAN joined the Telegraph Construction and Maintenance Co., Ltd., in 1870 and served a three years' apprenticeship with them, at the conclusion of which he joined the Eastern Telegraph Co., with whom, during a period of six years, he undertook the charge of the electrical arrangements of their Gibraltar station and assisted the late Mr. C. V. de Sauty in the first successful duplex experiments on long submarine cables. The almost continuous ill-health that so seriously handicapped Mr. Sullivan's career then made itself apparent, and he was invalided home, but with characteristic courage and determination he resumed his duties within a few months, and served with the staff afloat for two years. Rejoining the Telegraph Construction and Maintenance Co. in 1879 he assisted at many important cable-laying undertakings, including the Ireland–Newfoundland, Singapore–Batavia, Lisbon–Madeira duplicate, Suez–Aden triplicate, and the Straits of Sunda and Mozambique–Zanzibar duplicate. Subsequently he became associated with two French companies, La Compagnie Française des Cables Télégraphiques and La Société Industrielle des Téléphones, for whom he installed and organized a number of cable stations in various parts of the world. He served as electrician-in-chief and consulting engineer respectively during the manufacture and submersion of the last French Government cables between Marseilles and Tunis, and between the Australian Continent and New Caledonia. In 1897 Mr. Sullivan established himself in business in order to manufacture certain patented instruments, together with cable, testing, and telegraph signalling apparatus generally. The universal galvanometer which he invented and developed achieved instant and world-wide reputation, and the whole range of work he produced showed in a marked way the predominating characteristic of the man—that of taking infinite pains. The business steadily increased in prosperity and reputation, and in its administration Mr. Sullivan exhibited that rare combination of firmness and tact that has guided it through many difficulties and endeared him to those who have had the pleasure of working under him. The valuable assistance which he rendered to the Government in the early days of the war, mainly in the development of wireless telegraphy, laid the foundations of an extensive connection with the Home Departments and Foreign Governments, and with the expressed wish of providing for its continuance after his death, Mr. Sullivan in 1922 formed the business into a limited company. During the last few years it became clear that his health was so impaired that he should take more rest from the continuous detail work entailed by the company's ever-expanding activities, but his determination to continue was unbroken and he died, as he would have wished, in harness. He was elected an Associate of the Institution in 1878 and a Member in 1892. D. A. S.

HUGH LAWRANCE WILLIAMS received his education at Charterhouse and Trinity College, Cambridge, and from there went to Messrs. Thomas Parker, Ltd., where he was a pupil from 1896 to 1899. From 1900 to 1906 he was with Messrs. Lowdon Bros., leaving there to join the firm of J. G. White and Co. as constructional engineer. He became chief engineer to Messrs. Balfour, Beatty and Co., in 1909 on the foundation of the business, and was one of the principals of that firm from 1913, continuing in that position until his death, which occurred on the 25th July, 1925, at the age of 52. He was elected an Associate Member of the Institution in 1909 and a Member in 1918.

GEORGE MACDONALD WISE received his technical education at the Victoria Technical Institute and the Glasgow and West of Scotland Institute from 1893 to 1896. He then became a pupil in the shipbuilding firm of Wm. Denny and Brothers, Ltd., Dumbarton. He first went to sea as an engineer and afterwards joined the staff of the Bengal Iron and Steel Co. at Barrakar. In 1907 he became associated with Messrs. Tata, Bombay. Soon after Jost's Engineering Co., Ltd., electrical and mechanical engineers, Bombay, was formed, Mr. Wise became associated with it, first as assistant manager, then as manager, and finally as managing director, which office he held until his death on the 5th December, 1924. He was elected an Associate Member of the Institution in 1909 and a Member in 1922.

CHARLES HENRY WORDINGHAM, C.B.E., died on the 28th January, 1925. His friends in the Institution who had for some time taken a grave view of his illness, and the electrical world who were taken by surprise, heard with the deepest sorrow that Wordingham, a household name to all, had passed away. Born at Twickenham on the 14th April, 1866, his father being a medical man, he was educated at King's College School, and in 1882 entered the Engineering Department of King's College, London. Here he distinguished himself, being, as he always was, an indefatigable worker and throwing himself into not only the class-room and laboratory work, but also the social activities of the College. He was at one time secretary, and later president, of the King's College Engineering Society. He never lost his interest in "King's," and at the time of his death was on the council and delegacy of the College and president of the Old Students' Association.

On leaving King's College he was articled to the late Dr. John Hopkinson, F.R.S., and subsequently was with the United Telephone Co., but in 1889 he may be considered to have made his entry into the branch of the profession in which his future career was to lie, for in that year he became third engineer at the Grosvenor Gallery generating station of the London Electric Supply Corporation, in charge of the standardization department and the distribution substations. Perhaps it was here that his mind turned to standardization, a subject in which he eventually took so prominent a part.

In 1892 he joined Dr. John Hopkinson as assistant, and it was in this capacity that he was engaged on

the first lighting station of the Manchester Corporation. On the completion of the contract in 1894 he became the first City Electrical Engineer to the Manchester Corporation, a post which he held until 1901, during which time great developments took place. Before he left, his plan for a new combined tramway and lighting station with high-tension distribution was completed and was subsequently carried out by the Corporation.

In 1901 he left the Manchester Corporation and became a consulting engineer, carrying out certain Parliamentary work and work connected with company and municipal power and lighting schemes.

In 1903 he was appointed Head of the Electrical Engineering Department of the Admiralty, in which capacity he reorganized the electrical equipment of the Navy. It was no doubt his experience gained in electrical distribution on land that led him to adopt lead-covered paper-insulated cables for the principal mains on the larger ships. He introduced many entirely new features into the equipment and, no doubt, in some cases met with considerable opposition to his strong views.

Two matters outside his direct professional work were always in his mind. Standardization in the electrical world may almost be said to be his work. He was the driving force behind nearly every section of this work, and as a collateral activity was chairman of the Ship Electrical Equipment Committee of the Institution, and at the time of his death was also chairman of its Wiring Rules Committee. Another project at which he worked with great energy, arising from a need he had felt when he was with the Manchester Corporation, was a scheme for a Proving House to which appliances and material could be submitted to be tested as to their compliance with specified requirements. This scheme has not yet matured. He was a member of the Main Committee, and chairman of the Electrical Sectional Committee, of the British Engineering Standards Association, and a member of the British section of the International Electrotechnical Commission. He represented the Institution of Electrical Engineers on the General Board and Executive Committee of the National Physical Laboratory, was a member of the Council of the British Electrical Development Association, in the foundation of which the Institution co-operated, and he also represented the Institution on the Electrical Research Association, and was the first Chairman of the Council of the British Electrical and Allied Industries' Research Association, of which later he was the first President. He took a prominent part in the formation of the Incorporated Municipal Electrical Association and was its second President, serving in that capacity in 1896–97.

His connection with the Institution was a long one: he became an Associate in 1887, and a Member in 1894. He worked actively during the time he was in Manchester to strengthen the Institution in the provincial centres, and was Chairman of the Manchester Local Section, now the North-Western Centre, in 1901. He served on the Council from 1897 to 1902, from 1905 to 1908, and from 1909 to 1912; became Vice-President in 1914, was elected President in 1917 during the war period, and was re-elected President in 1918. His Presidential Address in 1917 outlined a scheme for the organization of the whole electrical profession and industry, and much that he then advocated has since been carried out. It was during this period that in the year 1918 he was created C.B.E., when he retired from the Admiralty and again became a consulting engineer, and he was still in practice at the time of his death.

He married in 1912 Emily Anne, daughter of the late Charles John West, J.P., of Queensland, and his wife and five children survive him.

His work at the Institution can be fully appreciated only by those on the Council and Committees of that body. No task was too great for the Institution he loved so well, and much of the great success and prosperity of the Institution of later years may be traced to his work. He advocated and prepared the way for the granting of the Charter by H.M. the King in 1921.

Of the man much might be written. In intellectual qualities he won through by sheer hard work rather than by brilliance; he studied every side of a question, and so prepared for himself the elements of every problem, and then logically developed the result that would follow, thus giving himself that clearness of prevision and foresight which he showed to such purpose. Once having made up his own mind he became an enthusiast to convert every opponent, every waverer. He found it difficult to see other people's point of view —a strength and yet a weakness. Those who worked with him in committee know how much time he spent in trying—often successfully—to convert a whole committee to his view. He occupied his mind little with abstruse questions of science or philosophy; essentially simple in his method of life, intensely practical in organization and management, satisfied with the religious faith of his forefathers, an ardent friend, a helper of younger men, he endeared himself to all. Many will remember his tender affection for his mother, who for many years accompanied him at the functions which he attended. About two years before his death he had a serious breakdown, but he was ill before this happened. The first sign to his friends who knew him well was when, at a dinner of an Association, he made a speech in which he practically despaired of the completion of the work of the Wiring Rules Committee, the first time he had ever been known to waver on a matter upon which he had set his heart. Possibly the work he undertook during the war had already overtaxed him. After the recovery from this breakdown he returned to his accustomed tasks, but he had lost power and was evidently working under difficulties; his holiday did not refresh him, a second breakdown followed, a long illness borne bravely and hopefully ended more suddenly than anyone expected, leaving to the Institution and his friends a memory that will long shine as an example and an inspiration. LL. B. A.

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EXPLANATION OF ABBREVIATIONS.

(P) indicates a reference to the general title or subject of a paper or address.
(p) indicates a reference to a subject dealt with in a paper or address of which the title is not quoted.
(D) indicates a reference to a discussion upon a paper or address of which the general title or subject is quoted.
(d) indicates a reference to a subject dealt with in a discussion on a paper or address of which the general title is not quoted.

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